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ADDITIVES FOR MODIFYING THE FROST SUSCEPTIBILITY OF SOILS

PART I

T. William Lambe
and
Chester W. Kaplar

March 1971

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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PREFACE

This report summarizes cooperative studies conducted over a three-year period (1952-1955) by the former Arctic Construction and Frost Effects Laboratory (ACFEL) of the U.S. Army Engineer Division, New England, and Dr. T. William Lambe of the Department of Civil Engineering, Massachusetts Institute of Technology. Dr. Lambe's services were obtained under renewing contractual arrangements (Contracts DA-19-016-ENG-1979, -2328, -2640, and -3213).

ACFEL and the U.S. Army Snow, Ice and Permafrost Research Establishment were combined to form the U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL), Hanover, New Hampshire, in 1961.

The study was conducted for the Engineering Division, Directorate of Military Construction, Office, Chief of Engineers, and was administered by the Civil Engineering Branch (Mr. F.B. Hennion, Acting Chief), in connection with Military Construction Investigations, Engineering Criteria and Investigations and Studies; Studies of Construction in Areas of Seasonal Frost. The Military Construction Investigations program is now conducted for the Office of Plans, Research and Systems (OPRS), Directorate of Military Construction, Office, Chief of Engineers.

Dr. Lambe was responsible for planning the scope of the investigation and assisted by furnishing the additives and preparing some soil admixtures. The freezing tests and preparation of data were performed by ACFEL personnel under the immediate supervision of Chester W. Kaplar, Project Engineer. The study was conducted under the general direction of Mr. Kenneth A. Linell, Chief, Experimental Engineering Division, USA CRREL (formerly Chief, ACFEL).

Lt. Col. Joseph F. Castro was Commanding Officer/Director of the U.S. Army Cold Regions Research and Engineering Laboratory during the publication of this report.

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CONVERSION TABLE

Multiply	*By*	*To Obtain*
Inches	25.4	Millimeters
Feet	30.48	Centimeters
Pounds	0.45359237	Kilograms
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Fahrenheit degrees	$\frac{5}{9}$	Centigrade or Kelvin degrees

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ADDITIVES FOR MODIFYING THE FROST SUSCEPTIBILITY OF SOILS, PART I

by

T.W. Lambe and C.W. Kaplar

INTRODUCTION

Background

When a moist soil is subjected to a low enough temperature the water within the soil freezes to form ice. If the soil moisture is *free* water, i.e. water not under significant attractive forces from the soil particles, it freezes at the normal freezing temperature of 0C. However, *adsorbed* water, that water under significant attractive forces from the soil particles, freezes at temperatures lower than 0C. Accompanying the water-to-ice phase transformation is a volume increase of approximately 10%. Upon freezing, therefore, a saturated soil can increase in volume by an amount equal to 10% of the void volume present.

To the consternation of civil engineers, however, a phenomenon occurs during freezing of certain types of soils that results in a volume increase far in excess of 10%. This phenomenon is the migration of soil moisture to form segregated ice lenses. Thus, freezing of a soil of this type can cause swelling or heaving many times greater than the amount that can be attributed to the volumetric change of void water. While much greater heaving is likely to occur when the freezing soil has access to an unlimited source of water nearby, considerable heave can also occur by a redistribution of moisture within a closed system. In such a system, the migrating moisture is replaced by air, or the soil consolidates (soil mass is compressed), or both.

Frost heaving in soil causes two major engineering problems. The soil expansion caused by frost heave moves structures that are in contact with the soil, such as building foundations, retaining walls, and pavements. Loss of pavement supporting capacity during thaw is of great concern to those responsible for design and maintenance of highways and airfields. Since the ground thaws chiefly from the surface down, the meltwater cannot easily drain downward because of the underlying frozen soil. This meltwater can make the soil wet and weak. Many base courses and subgrades lose most of their strength during the spring thaw and thus cause pavement failure.

Three conditions must exist simultaneously for frost heaving to occur: there must be a frost-susceptible soil, a prolonged period of freezing temperature, and a source of water. Since surface soils freeze and thaw seasonally in more than half of the Northern Hemisphere, frost action is a major concern of soil engineers. On many highway and airfield projects, the pavement design is controlled by frost considerations (Dept. of the Army, 1965). In areas where select granular non-frost-susceptible soils are unavailable, the construction of frost-resistant base courses becomes extremely expensive.

Purpose

These studies were part of a cooperative program between the Contractor, Dr. T.W. Lambe, and the Arctic Construction and Frost Effects Laboratory (ACFEL). The program had two major aims: to determine if any correlation existed between the mineralogical composition of the soil fines and the frost heaving behavior, and to find additives that would effectively reduce the frost susceptibility of soils. In this search for frost heave modifiers, attention has been chiefly concentrated on finding or selecting additives that would be effective in trace amounts (1% or less of

dry soil weight) for economic requirements, and which, by modifying the frost heaving characteristics of silty sand and gravels would make these materials satisfactory for base course construction.

Scope

This report summarizes the results of the first three years (1953-1955) of a continuing search for effective frost inhibiting additives. The search included extreme laboratory testing of the effectiveness of additives that theory and experience indicated might be promising frost heave modifiers. A small scale field test was conducted to further evaluate the effectiveness of one additive, a dispersant, that gave good results in the laboratory.

The findings of the mineralogical study phase of the overall program are summarized in USA CRREL Technical Report 207 (Lambe *et al.*, 1969).

THEORETICAL CONSIDERATIONS

General mechanisms

It has been clearly and convincingly demonstrated by Beskow, Taber and Casagrande that the presence of fines smaller than a certain critical size is the major factor in causing a soil to be frost-susceptible. But in addition to the fine particles, it must be possible for migrating water to reach the freezing front for ice lenses to form and grow. One of the most obvious methods of making a frost-susceptible soil non-frost-susceptible is to treat it in such a way as to immobilize the soil moisture and prevent it from migrating. However, our inadequate knowledge of soil moisture properties makes this solution difficult. Certain types, shapes or quantities of particles can in proper combination make a soil so impermeable that water cannot move rapidly enough under "normal" freezing rates. A coarse-grained soil, i.e. a clean sand or gravel, does not heave because it has few fines; nor does a highly plastic clay such as sodium montmorillonite heave appreciably under natural conditions, for an opposite reason: too many fines. In view of these observations, particle size appears to be an important parameter in ice lens formation, but not the only parameter. The precise relationships between frost susceptibility and other soil properties (such as permeability, void ratio, capillarity, particle shape, mineral composition and specific area) are not yet adequately understood or defined.

Other ways of reducing frost heave are: 1) to prevent freezing of the soil water and 2) to cement the soil particles together with a bond strong enough to resist the frost heaving force that is generated.

It is believed that additives are available that can accomplish each of the described treatments, e.g. reduce migration, lower the freezing point, and cement particles together. Some of the means by which additives can accomplish these effects are described below.

The legitimate question has been raised: "Can the results of a laboratory freezing test accurately indicate the frost behavior of a soil in the field, especially when the major problem is loss of strength upon thawing?" The answer is thought to be that the rate of heave does give an indication of the strength of a thawing soil. There are necessary qualifications to this statement of course. A great deal depends upon the rate and direction of thawing as well as the drainage characteristics of a particular situation; besides, all soils are not equally sensitive to moisture. One soil might heave a moderate amount but lose considerable strength upon rapid thawing; another might heave much more and yet have its strength diminished only slightly upon gradual thawing.

The cumulative effects of several immediately consecutive freeze-thaw cycles can be more serious in fine-grained soils than in coarse soils. The problem of thaw weakening is of significant importance. It is anticipated that investigations of the effects of additive treatment on the strength and other properties of thawing soil would need to be conducted in the laboratory and in the field to properly assess the overall worth of any frost heave modifier.

Primary functions of additives

Void filling. Completely plugging the voids of a soil with an impervious material prevents, of course, the movement of water. Asphaltic concrete and portland-cement concrete, having most of their voids filled, are not frost susceptible even though they may contain frost heave producing fines. The prevention of frost heaving in soils by this technique may be uneconomical; the soil in question might more cheaply be replaced with a non-frost-susceptible gravel or crushed stone.

Cementation. Closely related to the plugging of soil voids is the cementing of soil particles. The non-heaving characteristic of concrete is undoubtedly due to cementation as well as to its low permeability. As with void-plugging, the prevention of heaving by cementation can be uneconomical.

Alteration of void-fluid characteristics. The dissolving of additives in the soil water can result in a lowering of the freezing point of soil moisture. Sodium chloride and calcium chloride can reduce frost action by this mechanism. Lowering the freezing point reduces the depth of frost formation; it has little or no effect on the heave characteristics of freezing soil (see, for example, Yoder, 1955). An understanding of the nature of the forces involved in water migration to a growing ice lens might suggest other beneficial treatments by altering the soil water properties.

The most serious drawback to successful salt treatment of soil water is the impermanence of the treatment. A study in Massachusetts (Pyne, 1955; see Yoder, 1955) showed the effectiveness of calcium chloride treatment of a subgrade to be about 3 years. Since stability considerations require that base course soils be free-draining, the void liquid in these soils is probably soon leached out by the movement of ground water. The leaching of salts from fine-grained subgrade soils can take considerably more time.

Aggregation of soil fines. As already noted, a soil containing fine particles is likely to be frost susceptible to some degree. Casagrande (1932) set this as a minimum of 3% by weight finer than 0.02 mm size. While soils have been encountered that possess less than this amount but still are frost susceptible, no better criterion, other than one based on laboratory freezing tests, has yet been found.

A frost-susceptible soil can be made essentially non-frost-susceptible by removing the fines. This principle has been employed by the U.S. Army Corps of Engineers on several of their major airfield construction projects in northern New England where the fines were washed out from "dirty" base course materials.

The effect of fines in a soil can be modified with additives that cause small particles to aggregate into larger units. Either conventional cements (e.g. portland cement) or chemicals that cause flocculation by electrochemical reactions can be used in this way to nullify the effect of the fines. Michaels (1952) hypothesized on the various means by which aggregants, especially the synthetic polymers, flocculate soil fines. The polymers usually exist as long-chain molecules whose ends can attach themselves to the soil mineral surfaces. The particles are thus linked together by the polymer chains.

Synthetic polymers have been marketed as "soil conditioners" for the improvement of agricultural properties of soil (primarily by increasing the porosity and permeability). Even though the polymers are effective in trace quantities, their high unit cost ($\geq$50¢/lb) has greatly hindered their use.

Soil aggregation can also be obtained by polyvalent cations such as Fe^{+++} and Al^{+++}. These cations act by shrinking the diffuse double layers around the soil colloids enough to permit the interparticle attractive forces to cause the particles to cohere. Another phenomenon, ion fixation, comes into play with certain ions to greatly increase their aggregating ability. The most notable example is ferric iron, Fe^{+++}. If Fe^{+++} is added to a fine-grained soil, an ion exchange reaction can occur where the iron replaces some of the exchangeable cations on the soil particles. This reaction tends to produce flocculation because of the reduction of the interparticle repulsive charges (Michaels and Lambe, 1953). If the ionically altered soil is dried, some of the iron ions link adjacent particles together with a very strong bond that is resistant to water attack. These ions become "fixed" and are no longer exchangeable. When the iron is added to the soil as a chloride salt ($Fe\,Cl_3$), the formation of iron hydroxide is possible; iron hydroxide can be a weak cement.

Considerable study (e.g. Lambe and Martin, 1954) has shown that when natural clays containing iron are dried they are considerably less plastic and have only a fraction of the fines that would be expected from their mineralogical composition. For example, a clay from Jamaica had 60% by weight of clay mineral matter but only 20% by weight of particles finer than 0.002 mm. The 2.3% iron oxide (Fe_2O_3) the clay contained effectively made silt sizes out of most of the clay minerals.

Alteration of water-adsorbing characteristics of soil fines. If the soil surface characteristics that control the behavior of soil moisture films were fully known, the characteristics could possibly be altered. Mineral surfaces can be made hydrophobic with the proper additives in two ways. 1) the soil may be treated with a substance made up of molecules, one end of which is first preferentially adsorbed on the mineral surface and then undergoes an irreversible reaction with the surface, while the other end is hydrophobic and thus makes the mineral surface non-wettable by water. 2) The soil may be treated with non-hydratable cations, such as lead and mercury, that are attracted to the negatively charged soil particles. A soil can thereby be waterproofed so it cannot be wetted.

Dispersion of soil fines. Just as there are chemicals that can aggregate soil fines, so there are other chemicals that can do the reverse, namely, disperse some of the natural agglomerations of soil fines. Most of these chemical dispersants are made up of a polyanionic group, e.g. phosphate or sulfonate, and a monovalent cation, usually sodium. Some of the anionic groups can remove any polyvalent cations by forming insoluble products, and others can become attached to the soil-mineral surface. The sodium ions become linked to the soil, replacing the removed polyvalent exchangeable cations.

Both the cation exchange, monovalent or polyvalent, and the anion adsorption expand the diffuse double layers around the soil colloids, thus increasing interparticle repulsion. This increase of interparticle repulsion tends to disperse the agglomerations of soil fines. Particles that do not stick together can be manipulated into a more orderly and denser structure. Concomitant with improved structure are higher density, lower permeability, and higher stability to water. These and other alterations of soil properties that can be effected by trace quantities of chemical dispersants have been described by Lambe (1954).

Since dispersants can alter soil properties that are related to frost susceptibility, they should affect the frost susceptibility of a soil. By decreasing the sizes of soil voids, dispersants are also beneficial in lowering the freezing temperature of soil moisture.

The preceding theoretical considerations guided the selection of additives evaluated as frost-heave modifiers. Many, in fact most, of the additives used perform more than one of the functions described; for example, to be an effective dispersant a chemical must alter the characteristics of the surfaces of soil particles. While all the additives should, under certain circumstances, alter the frost characteristics of soil, the efficiency of each must be determined by actual freezing tests.

TEST PROGRAM

Additives

Table I lists the 52 additives evaluated as frost-heave modifiers. They are classified as follows: 1) void fillers and cementing agents, 2) aggregants, 3) metallic salts, 4) waterproofers, and 5) dispersants. The grouping is by primary function except for the metallic salts which can interact with soil fines as aggregants or waterproofers.

Soils

Table II describes the 25 soils used in the additive evaluation program. They range from highly plastic clays to sandy gravels and represent a good sampling of frost-susceptible soil types.

Test procedure

Test sequence. The freezing test program had three phases. The first, laboratory screening, was aimed at selecting promising frost-heave modifiers from the many additives that theory suggested might be effective. Miniature Lucite molds 3.11 in. high and 1.25 in. in diameter were frozen in groups of 36 in a special freezing tray (Fig. 1) over a short time interval. Most of the freezing tests on these miniature specimens were run on three soils, New Hampshire silt, Fort Belvoir sandy clay, and Boston blue clay, selected to give a range of frost-susceptible soil types.

Promising additives were evaluated further using different soils and a standard size Lucite mold, 6.0 in. high and 5.91 in. in diameter. The freezing cabinets accommodated four of the larger specimens at a time. The larger size permitted the testing of coarser-grained frost-susceptible sands and gravels of the type that would be acceptable as base and subbase materials were it not for their frost-heaving characteristics.

The third step in the investigation was small-scale field testing of one promising additive, a dispersant.

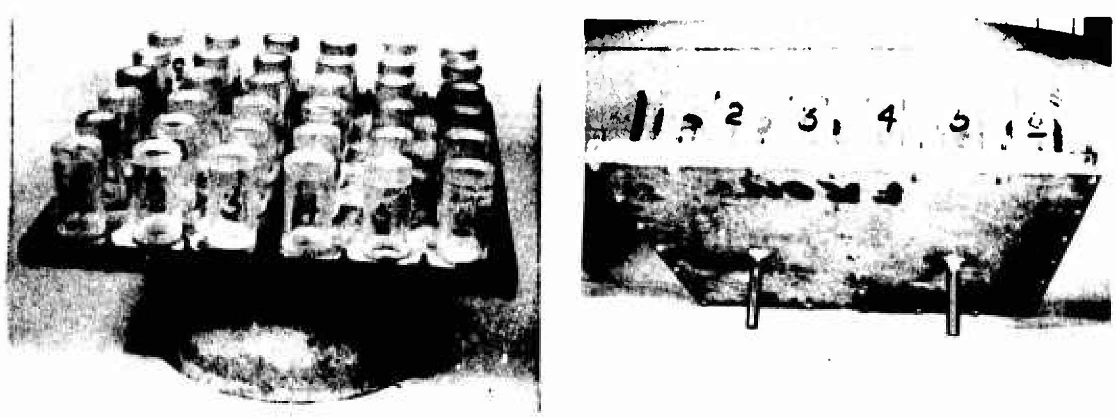


Figure 1. Miniature specimen freezing tray.

Table I. Additives tried as frost-heave modifiers.

Item	Class	Additive	Registered Trademark	Supplier	Price, 1966* ($/lb)	Form
	Void fillers and cementing agents					
1	Synthetic polymer	Calcium acrylate		Carbide and Carbon Chemical Company, New York, N.Y.	2.00	Liquid
2	Resin-type additives	Vegetable pitch 250		General Mills, Inc., Minneapolis, Minn.		Liquid
3		Tall oil 50		General Mills, Inc., Minneapolis, Minn.		Liquid
4		Vegetable residue		General Mills, Inc., Minneapolis, Minn.		Liquid
5		Polyamide resin 100		General Mills, Inc., Minneapolis, Minn.		Liquid
6		Asphalt (emulsion, 68% solids)		American Oil Products Company, Somerville, Mass.	0.60	Liquid
7	Cementing agent	Portland cement			0.03	Powder
8	Natural fines	Sodium montmorillonite		(Wyoming bentonite)	0.015	Soil fines
9		Peat fines		(Natural deposit, northeastern, Mass.)	0.03	Organic fines
	Aggregants					
10		Modified starch	Flocgel	W.A. Scholten's Chemische Fabrieken N.V., Foxhol, Nederland	0.12†	Powder
11		Sodium salt of a polymer	CRD-197**	Monsanto, Everett Station 49, Boston, Mass.		Powder
12		Polygaloctomannan	Guartec	General Mills, Inc., Minneapolis, Minn.		Powder
13		Maleic polymer (soil conditioner)	Krilium #6	Monsanto, Everett Station 49, Boston, Mass.		Powder
14		Sodium polyacrylate	Agrilon	Borden Chemicals, Div. of Borden, Inc., New York, N.Y.		Solution, flakes
15		Copolymer of styrene and methosulfate		Koppers Company Inc., Pittsburgh, Penn.		
16		Polyvinyl alcohol (PVA)		E.I. duPont deNemours & Co., Industrial & Bio-Chemicals Dept., Wilmington, Del.	0.50	Powder
17	**Metallic salts** (Aggregants and waterproofers)	Ferric chloride		Mallinckrodt Chemical Works, St. Louis, Mo.	0.08	Crystalline
18		Ferric sulfate		Mallinckrodt Chemical Works, St. Louis, Mo.	0.02	Crystalline
19		Lead acetate		Mallinckrodt Chemical Works, St. Louis, Mo.	0.27	Crystalline
20		Barium acetate		Mallinckrodt Chemical Works, St. Louis, Mo.	0.15	Crystalline
21		Potassium chloride		Mallinckrodt Chemical Works, St. Louis, Mo.	0.17	Crystalline
22		Mecuric chloride		Mallinckrodt Chemical Works, St. Louis, Mo.	>2.00	Crystalline
	Waterproofers					
23		Sodium methyl siliconate	SC-50	General Electric Co., Silicone Products Dept., Waterford, N.Y.	0.67	Solution
24		Sodium methyl ethyl propyl siliconate		Dow Corning Corp., Midland, Mich.		Solution
25		Potassium phenyl siliconate		Monsanto, Everett Station 49, Boston, Mass.		
26		Stearyl dimethyl benzyl ammonium chloride	Triton K-60††	Rohm and Haas Co., Philadelphia, Pa.		Paste
27		Methacrylato chromic chloride	Volan	E.I. duPont deNemours & Co., Industrial & Bio-Chemicals Dept., Wilmington, Del.	1.48	Liquid
28		Stearato chromic chloride	Quilon	E.I. duPont deNemours & Co., Industrial & Bio-Chemicals Dept., Wilmington, Del.	0.55	Liquid
29		Quaternary ammonium chloride	Hyamine 1622	Rohm and Haas Co., Philadelphia, Pa.	0.57	Solution
30		Quaternary ammonium chloride	Hyamine 2389	Rohm and Haas Co., Philadelphia, Pa.	0.41	Solution
31		Triethylene tetramine		Eastman Kodak Company, Rochester, N.Y. (Distributor: Howe and French, Boston, Mass.)	>2.00	Liquid
32		Hexamethylene diamine		Eastman Kodak Company, Rochester, N.Y. (Distributor: Howe and French, Boston, Mass.)	0.17	Liquid
33		Di-N-Butylamine		Olin Mathieson Chemical Corp., East Rutherford, N.J. (Distributor: Howe and French, Boston, Mass.)		Liquid
34		Tertiary alkyl primary amine	Primene 81-R	Rohm and Haas Co., Philadelphia, Pa.		Solution
35		Polyethylene glycol	Carbowax Peg 200	Union Carbide Corp., New York, N.Y.	0.33	Liquid
36		Polyethylene glycol	Carbowax Peg 6000	Union Carbide Corp., New York, N.Y.	0.36	Granular
37		Dioctadecyl dimethyl ammonium chloride	Arquad 2 HT	Armour Industrial Chemical Co., Chicago, Ill.	0.34	Solution
38		Octadecyl amine	Armeen 18 D	Armour Industrial Chemical Co., Chicago, Ill.	0.63	Solution
39		Diethanol rosin amine D acetate		Hercules Powder Company, Wilmington, Del.		
40		Monoethanol rosin amine D acetate		Hercules Powder Company, Wilmington, Del.		
	Dispersants					
41		Tetrasodium pyrophosphate (TSPP)		Westvaco Chemical Company, New York, N.Y.	0.12	Powder, granular
42		Sodium tetraphosphate	Quadrafos	Rumford Chemical Works, Rumford, R.I.	0.12	Powder, granular
43		Sodium hexametaphosphate		Westvaco Chemical Company, New York, N.Y.	0.14	Powder, granular
44		Sodium tripolyphosphate		Westvaco Chemical Company, New York, N.Y.	0.08	Powder, crystalline
45		Sodium salt of ethylene diamine Tetra acetic acid	Versenate	The Dow Chemical Company, Midland, Mich.		
46		Sodium salt of carboxylic acid	Tamol 731	Rohm and Haas Co., Philadelphia, Pa.	0.23	Granular
47		Formaldehyde-condensed naphthalene sulfonates	Daxad 11	W.R. Grace and Co., Cambridge, Mass.	0.26	Powder
48		Mono-calcium salt of polymerized Naphthalene sulfonates	Daxad 21	W.R. Grace and Co., Cambridge, Mass.	0.23	Powder
49		Lignosulfonate salts	Marasperse N	American Can Co., Chemical Products 2A1, Greenwich, Conn.	0.11†	Powder
50		Lignosulfonate salts	Marasperse C	American Can Co., Chemical Products 2A1, Greenwich, Conn.	0.07†	Powder
51		Lignosulfonate	Lignosol	Lignosol Chemicals, Quebec, P.Q., Canada	0.05†	Solution, powder
52		Calcium lignosulfide	Pozzolith	Master Builders Company, Waltham, Mass.	0.35	Powder

* No recent data available. ** Unregistered trademark.
† Estimated. †† Now X-400

Table II. Physical properties of soils used in additive evaluation program.

Item	Lab. serial no.	Specimen designation	Source	Material (Unified Soil Classification System)		Gradation as tested % finer (U.S. standard sieve)						Compaction		Atterberg limits[6]		Sp gr (total sample)	Permeability		Composition of minus 0.074 mm soil fraction[9]			
				Description	Symbol	Max. size (in.)	4.76 (mm)	0.42 (mm)	0.074 (mm)	0.02 (mm)	0.002 (mm)	Max. dry unit wt. (lb/cu ft)	Opt water content (%)	LL (%)	PI (%)		Void ratio	k × 10^{-4} cm/sec at 10C	Mineral	(%)	Organic matter (%)	Glycol retention of soil (mg/g)
1	B-11	DFB	Dow AFB, Bangor, Maine	Sandy gravel	GW	¾	42	13	4.9	2.4	<1	137.6[3]		Non-plastic		2.70	0.300	16.0				14 (est)
2	TP-250 (50-54-9)	PBJ	Project Blue Jay, Greenland	Sandy gravel	GW	¾	38	18	4.0	1.7	<1	148.2[8]		Non-plastic		2.72	0.212	1.6	Illite Chlorite Montmorillonoid Feldspar Quartz Free iron oxide	15* 15* 5* 40 20 3	1.4	24
3	B-18	DFSB	Dow AFB, Bangor, Maine	Silty sandy gravel	GW-GM	¾	49	17	8.0	3.2	<1	138.8[3]		Non-plastic		2.69	0.290 0.270	6.2 4.6				14 (est)
4	49-49	LSG	Loring AFB, Limestone, Maine	Silty sandy gravel	GW-GM	¾	47	17	9.5	6.8				Non-plastic		2.71	0.250 0.213	0.3 0.1	Kaolinite Illite Limonite Magnesite	40 20 5 5	<1	14
5	49-30	LSG	Loring AFB, Limestone, Maine	Silty sandy gravel	GW-GM	1	48	9	5.6	4.6	2.5	139.1[2]		Non-plastic		2.71	0.380 0.290	≥73 100	(Approximately as above)			
6	49-87	LST (Standard and Miniature)	Loring AFB, Limestone, Maine, Subgrade Frost Test Section)	Clayey sandy gravel (Glacial till)	GC	2	68	52	41	30	10	136.9[5]	7.5	21-22	6-8	2.73			Kaolinite Illite Quartz Mica Carbonates	30 15 30 <5 2	1.5	14
7	49-8 and 49-8A	CL	Clinton County AFB, Wilmington, Ohio	Silty clayey gravel	GM-GC	1½	53-54	25-30	15-20	9.0-15	2.0			25	7	2.72	0.480 0.400 0.320	10 1.0 0.1	Illite Vermiculite Dolomite Feldspar Quartz Free iron oxide	20* 15* 25 20 10 2	<1	27
8	49-21	SPK	Spokane AFB, Spokane, Washington	Gravelly sand	SW-SM	1½	68-69	11	7.0	3.5	<1			Non-plastic		2.80	0.410 0.310	100 10	(No carbonates)		2.2	27
9	49-102	LIN	Lincoln AFB, Lincoln, Nebraska	Gravelly sand	SP-SM	¾-1	67-71	24-27	6.3-7.8	5.0	2.5	133.0[4]		Non-plastic		2.65						
10	49-11	RC	Ellsworth AFB, Weaver, South Dakota	Silty gravelly sand	SW-SM	1½	57	30	12	8.7	2.5			19	2	2.75	0.390 0.330	10 1.0	Carbonates	15	1.5	44
11	49-55	(Miniature)	Pease AFB, Portsmouth, New Hampshire	Silty sand (Portsmouth sand)	GM	¾[2]	98	94	29	8.2	2.5	111.6[4]	12.5	Non-plastic		2.72	0.826 0.761 0.526	20 14 3.0	Illite Chlorite Quartz Feldspar	10 3 35 50	<1	5
12	49-54	PAFB	Pease AFB, Portsmouth, New Hampshire	Silty gravelly sand	SM	¾	68	45	23	14	3.0	128.6[3]		Non-plastic		2.70			(No carbonates)		<1	14
13	49-17	SF	Sioux Falls Airfield, Sioux Falls, South Dakota	Silty clayey gravelly sand	SM-SC	1	71-75	28	15-16	8.0-9.0	2.5			24	6	2.70	0.600 0.490 0.292	100 10 0.16	Carbonates	17	1.2	40
14	49-60	WWS	Fairchild AFB, Spokane, Washington	Silty clayey gravelly sand	SM-SC	¾	76-88	29-33	17-19	9.5-10	2.5-5.0	142.1[2]		22-25	3-6	2.77						
15	49-9	PT	Patterson AFB, Fairfield, Ohio	Silty clayey gravelly sand	SM-SC	1½	62-63	33-34	21-22	15	3.0			22	6	2.72	0.400 0.360 0.267	10 1.0 0.001	Illite Quartz Dolomite Limonite	40 35 20 5	2.3	22
16	49-91	BH	Breed's Hill, Orient Heights, Boston, Mass.	Clayey gravelly sand (Breed's Hill or East Boston Till)	SC	¾	76	60	41	24	8.5	138.5[5]	7.4	24	11	2.76	0.475	0.02	Illite Kaolinite Quartz Feldspar, mica and limonite	20 20 30 <5	<1	26

Table II (cont'd).

Item	Lab. serial no.	Specimen designation	Source	Material (Unified Soil Classification System): Description	Symbol	Gradation as tested % finer (U.S. standard sieve): Max size (in.)	4.76 (mm)	0.42 (mm)	0.074 (mm)	0.02 (mm)	0.002 (mm)	Compaction: Max. dry unit wt. (lb/cu ft)	Opt water content (%)	Atterberg limits[8]: LL (%)	PI (%)	Sp gr (total sample)	Permeability: Void ratio	k × 10⁻⁴ cm/sec at 10C	Composition of minus 0.074 mm soil fraction[9]: Mineral	(%)	Organic matter (%)	Glycol retention of soil (mg/g)
17	49-63	(Miniature)	Field Research Area, Fairbanks, Alaska	Silt (Fairbanks silt)	ML-OL		100	100	95	35	6.0	112.5^4	15.7	26-33	4-6	2.68	0.556	0.17	Illite Vermiculite Quartz Free iron oxide (No carbonates)	20* 27* 35 1	1.7	17
18	(MIT M-21 Soil)	(Miniature)	Revere, Massachusetts	Clayey silt (Mass. clayey silt)	ML-CL		100	88	83	40	12	122.3^6	1.33	20	6	2.77			Illite Quartz Feldspar Free iron oxide	30 35 20 3		21
19	49-46	NH (Standard and Miniature)	Goff's Falls, New Hampshire	Clayey silt B (N.H. silt)	ML-CL		100	100	99	[illegible]	6.0	110.1^4	14.7	24	6	2.74	1.000 0.800 0.551	0.8 0.3 0.1	Illite Quartz Feldspar Mi (No carbonates)	10 40 40	1	[illegible]
	49-5			Silt A	ML		100	100	25	62	7.0	98.6^6	21.0	25	7		1.000 0.800	0.388 0.10				
20	49-88	PAFB	Pease AFB, Portsmouth, New Hampshire	Sandy clay	CL		100	98-99	89-91	88	13			28	12	2.70						
21	49-66	FB (Standard and Miniature)	Fort Belvoir, Virginia	Sandy clay (Fort Belvoir sandy clay)	CL	¾[2]	95-97	88	62-64	43-46	25-28	107.6^6 115.0^4	18.5 16.1	41	19	2.73	1.000 0.500	2.0 0.2	Kaolinite Quartz Hydrous oxides of iron and aluminum	25 40		26
22	49-65	(Miniature)	WASHO Test Road Malad, Idaho	Clay (WASHO clay)	CL-OL		100	100	96	65	21	99.6^4	21.0	37	13	2.58			Illite Montmorillonoid Carbonates Free iron oxide Trace of quartz	13* 12* 15 1.5	2.7	62
23	49-42	(Miniature)	North Cambridge, Massachusetts	Clay (Boston blue clay)	CH		100	100	100	94	67	108.2^6	20.2	53	26	2.78	0.917 (remolded)	0.001	Illite Quartz Limonite Feldspar and mica	40-50 15-25 5 < 5		11
24	49-78-3	(Miniature)	Niagara Falls AFB, Niagara Falls, N.Y.	Clay (Niagara Falls clay)	CH		100	100	100	96	65-78	108.2^5	18.0	60	37	2.79			Carbonates	22	< 1	40
25	50-58	(Miniature)	Fargo Municipal Airport, Fargo, North Dakota	Clay (Fargo clay)	CH-OH		100	100	98	85	50	101.5^7	22.0	68-71	46-47	2.76	0.980	0.2	Montmorillonoid Illite Quartz Carbonates Free iron oxide	30* 25* 15 10 4	1.3	100

1. Freezing test specimens were 6 in. high, 5.9 in. diam. unless otherwise noted.
2. Soil for miniature specimens scalped through U.S. Standard No. 10 sieve (2.0 mm). Miniature specimens 3.1 in. high, 1.25 in. diam.
3. Providence Vibrated Density Test: 7-in.-diam steel cylinder, 1000 lb static load, vibrated by blows of 2½-lb hammer over exterior walls.
4. Modified AASHO Density Test: $\frac{1}{30}$-cu-ft cylinder, 5 layers, 25 blows per layer, 10-lb tamper, 18-in. drop.
5. ASTM Designation T180-57, Method D except $\frac{1}{30}$-cu-ft cylinder, 55 blows per layer. ¾ in. material replaced by material between #4 and -¾ in. sieves.
6. Harvard Miniature Compaction Test: $\frac{1}{454}$-cu-ft cylinder, 3 layers, 25 tamps per layer, 40-lb prestressed spring tamper, minus 2.0 mm soil fraction.
7. Modified Harvard Miniature Compaction Test: same as 6 except 60 tamps per layer.
8. Limits performed on material passing U.S. Standard No. 40 sieve.
9. (a) * Denotes interstratified minerals. (b) Minerals determined by differential thermal analysis and X-ray diffraction. Free iron extracted by Na_2SO_4 and expressed as Fe_2O_3. (c) Organic matter determined by H_2SO_4 - $K_2Cr_2O_7$ oxidation method. (d) Ethylene glycol retention a measure of surface area. One mg glycol covers area of approximately 3.2 sq m. (e) Composition analyses shown for Items 16 and 19 based on tests performed on following soil samples: Item 16, East Boston Till, Lab. Ser. Nos. 49-2 and 49-43, approximately equivalent to Lab. Ser. No. 49-21. Item 19, New Hampshire Silt, Lab. Ser. No. 49-105, approximately equivalent to Lab. Ser. No. 49-46.

Specimen preparation. Untreated specimens were prepared at water contents approximating optimum for the compaction method used. Miniature specimens were compacted in three layers with 60 tamps per layer of a 40-lb spring-stressed tamper. Standard specimens were compacted in a variety of ways, depending upon the cohesive qualities of the soil. Coarse-grained, relatively cohesionless soils were prepared using an adaptation of the Providence Vibrated Test. Fine-grained soils were compacted either by static double-end compression or by adaptations of the Modified AASHO Test. The methods have been described previously (ACFEL, 1953).

The preparation of treated specimens depended upon the nature of the additive being evaluated. In the great majority of tests the additive was added with the molding water. Additives such as portland cement and asphalt emulsion were pre-mixed with the air-dry soil. All the miniature specimen batches and most of the standard-size batches were thoroughly mixed by hand until homogeneous. Cement-treated standard-size soil batches were blended with a mechanical mixer. The compaction techniques were the same as those described above. Some of the compacted specimens, notably those with portland cement and asphalt emulsion, were cured prior to freezing, but most were frozen without curing. Tables AI-AV in the Appendix present freezing-test data on all specimens tested in FY 1955, and show the various methods used to prepare the specimens.

The specimens were saturated and placed in a freezing chamber with a free water surface maintained approximately ¼ in. above a porous stone at the bottom of each specimen. The standard-size specimens were tested under an applied dead load of 0.5 psi to simulate field conditions consisting of a 6-in. combined thickness of base and pavement. Thermocouples were placed in several specimens in each freezing cabinet to permit control over the rate of freezing. Granulated cork insulating material was packed around the specimens for their full height.

Specimen freezing. After equilibrating for 1 day, the specimens were frozen from the top down by gradually decreasing the air temperature above them while maintaining the temperature at the bottom end between 35 and 38F. The temperature above the specimens was lowered daily to obtain approximately ¼ in. penetration per day of the 32F isotherm into the specimen – a rate of penetration found conducive to severe ice segregation in the field. A daily record was kept of the heave of each specimen. At the end of the freezing period each specimen was examined to ascertain the depth to which it was frozen. The final water-content distribution in each specimen was then determined.

Evaluation procedure. The average rate of heave, in millimeters per day, was determined from a portion of the heave versus time plot in which the slope was relatively constant and during which the penetration of the 32F isotherm was relatively linear and between ¼ in. and ¾ in. per day. The heave was averaged over a minimum of 5 consecutive days.

The method of evaluating frost susceptibility in terms of the average rate of heave or the relative amount of heave with respect to the original depth of the frozen portion means that none of the beneficial effects of the additives can be attributed to a lowering of the freezing point of the pore water. Since alteration in frost characteristics is needed to evaluate an additive, the average rate of heave of a treated specimen was divided by the average rate of heave of an untreated specimen (control). The value obtained is termed ***heave ratio*** and is a measure of heave alteration since a ratio <1 indicates improvement and a ratio >1, impairment.

Studies made at ACFEL (1950, 1951, 1953) and published by Linell and Kaplar (1959) have shown that frost heave varies with many test conditions, such as molding moisture, compacted density, load pressure on sample and rate of freezing. In the tests described here an attempt was made to control these variables to permit the effects of the additives to be isolated and studied. Since either 36 miniature or 4 standard-size specimens were frozen in the same cabinet, the rate of frost penetration could actually be controlled at ¼ in./day in only one specimen. To minimize the differences in penetration rates, all specimens in a cabinet, whenever possible, were prepared from the same soil. With each group at least one untreated specimen was frozen.

In the screening tests of the miniature specimens, the reproducibility of results within a given tray of 36 specimens was good. For example, one tray frozen had five specimens of untreated Fort Belvoir sandy clay with heaves of 1.46, 1.49, 1.53, 1.59 and 1.84 mm/day. However, in another tray, where the freezing rate was controlled from thermocouples in New Hampshire silt, untreated Fort Belvoir sandy clay heaved 2.74 mm/day. When different soils were frozen in the same tray, at least one control specimen was included for each soil. The average rate of heave of this control specimen (or the average of the average rates of heave where more than one control was included) was used to compute the heave ratios of treated specimens of that soil in the tray.

Because of the difficulties of controlling the many variables, especially freezing rate, the heave rates are probably no better than ± 15%. Since the miniature specimen tests were only used to screen out the many additives studied, this reproducibility is acceptable.

TEST RESULTS

Presentation of results

Data on the preparation and freezing of specimens tested in FY 1955 are presented in the Appendix. Tables AI and AII contain data on the laboratory screening tests using miniature specimens. Tables AIII-AV contain data on standard-size specimens.

Some typical data on the daily heave and freezing temperature penetration are presented in Figure A2.

Similar data pertaining to the FY 1952-1954 investigations have been presented in a previous report (ACFEL, 1953).

The test data most pertinent to the discussions below are summarized in Figures 2-7 and Tables III-XII.

Void fillers and cementing agents. This category includes those additives whose primary function is either to plug (seal) soil voids or to cement soil particles. Most of them do both, as well as perform other functions described previously.

To completely plug the voids in a soil would require an inordinate amount of additive; for example, the void ratios of most of the compacted soil specimens varied from about 0.5 to 1. To fill these voids would have required a volume of additive varying from 0.5 to 1 times the volume of soil grains. Effective sealing may, in some instances, be accomplished at a lower level of treatment by plugging only some of the voids.

Because of the large amount of pluggers and cementers required, only very cheap additives offer promise. Attempts were made to increase the effectiveness of cements with trace additives. The water-sensitive void pluggers were tried since they can utilize void water to help make up the volume needed to seal the soil particles.

A disadvantage of most sealers and cements is that a reaction is required after their addition to the soil, e.g. hydration of portland cement, breaking of asphalt emulsion, and polymerization of calcium acrylate. The specimens containing these materials were, therefore, cured before freezing.

Synthetic polymer. Research at the Massachusetts Institute of Technology (Lambe, 1951), sponsored by the Arctic Construction and Frost Effects Laboratory, indicated that the *in situ* polymerization of monomers, especially calcium acrylate, changed soil properties significantly (Haley, 1953). Figure 2 shows that 5% calcium acrylate essentially prevented frost heave in Fort Belvoir sandy clay and that 10% prevented heave in New Hampshire silt.

Acrylate stabilization was developed for emergency military conditions; its cost is too great for large-scale non-emergency use at other than trace-level treatments.

Sample no.	Material	% Ca acrylate	Grain size mm - % finer 2.0	0.42	.074	0.02	% heave[1]	Avg rate of heave (mm/day)	Heave ratio[2]	Dry unit weight (lb/ft³)	Void ratio	Perme-ability k × 10⁻⁴ (cm/sec)	Atterberg limits[3] LL	PI
NH-29-A	New Hampshire silt	0	99	93	85	73	235.3	14.0	1.0	101	0.674	0.036	26	5
NH-28-A		5	99	93	85	73	43.8	4.5	3.2	101	0.662		26	5
NH-27-A		7.5	99	93	85	73	12.8	2.0	0.14	101	0.662		26	5
NH-26-A		10	99	93	85	73	7.7	0.5	0.03	102	0.649		26	5
FB-1-A	Fort Belvoir clay	0	97	89	63	49	188.4	14.0	1.0	110	0.536	0.148	39	17
FB-2-A	(-¼ in.)	5	97	89	63	49	0.0	0.0	0	111	0.516		39	17
FB-3-A		7.5	97	89	63	49	1.2	0.1	< 0.01	109	0.557		39	17
FB-4-A		10	97	89	63	49	2.7	0.1	< 0.01	105	0.610		39	17
NH-33-A	New Hampshire silt	5	100	96	90	67	30.9[4] 27.5[5]	3.3[4] 3.1[5]	0.24 0.22	98	0.712		[illegible]	6
NH-34-A		5	100	96	90	67	26.[illegible][4] 23.9[5]	3.0[4] 3.2[5]	0.21 0.23	97	0.739		25	6
FB-5-A	Fort Belvoir clay (-¼ in.)	5	97	89	63	49	1.3[4] 1.0[5]	0.1[4] 0.1[5]	< 0.01 < 0.01	102	0.654		39	17
FB-6-A		5	97	89	63	49	1.8[4] 0.0[5]	0.1[4] 0.0[5]	< 0.01 0	102	0.650		39	17

1. Based on original height of frozen portion.
2. Ratio of rate of heave of treated specimen to that of untreated specimen.
3. Tests made on material passing the U.S. Standard No. 40 sieve.
4. First freezing cycle.
5. Second freezing cycle.

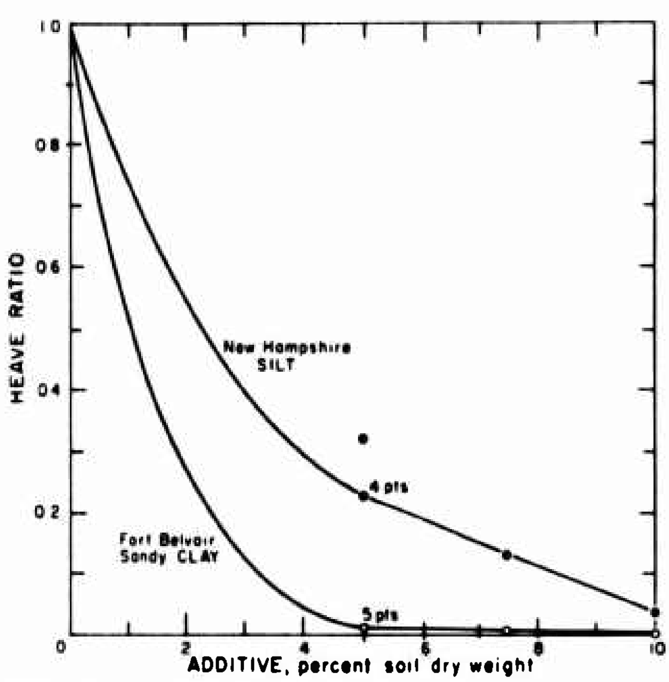


Figure 2. Effect of calcium acrylate on frost heave. All specimens were close to 100% saturation at start of test.

Resin-type additives. Table III lists the heave ratios of soils treated with each of five resin-type additives. Since the four non-asphalt additives contain anti-stripping type components, they do not require the soil to be predried as much to get good soil/additive bonding as does asphalt. This advantage does not show in Table III since all specimens were dried before and after treatment.

Table III. Summary: effect of resin-type additives on frost heave (miniature specimens).

Additive		Heave ratio*			
Type	%	Boston blue clay	New Hampshire silt	Fort Belvoir sandy clay	Massachusetts clayey silt
Vegetable pitch 250	0.50	0.89, 0.46	0.52, 0.82	0.76, 0.73	0.98
	1.00	0.75, 0.91	0.72, 1.01	0.85, 0.55	1.14
	3.00	0.67, 1.10	0.94, 1.27	0.34, 0.40	0.60
Tall oil 50	0.50	0.73	0.48	0.65	0.92
	1.00	0.73	0.24	0.48	0.84
	3.00	0.64	0.25	0.37	0.66
Vegetable residue	0.50	0.73	0.34	0.78	0.54
	1.00	0.69	0.50	0.75	0.95
	3.00	0.88	0.33	0.42	1.14
Asphalt (Emulsion, 68% solids)	0.50	0.54	0.43	0.32	
	1.00	0.98	0.60	0.34	
	3.00	0.43	0.53	0.52	
Polyamide resin 100	0.10	0.59		1.03	
	1.00	1.78		0.98	
	3.00	1.84		1.22	

$$* \text{ Heave ratio} = \frac{\text{avg rate of heave of treated soil}}{\text{avg rate of heave of untreated soil}} .$$

Table IV. Summary: effect of portland cement on frost heave (miniature specimens).

Additive		Heave ratio		
Type	%	Boston blue clay	New Hampshire silt	Fort Belvoir sandy clay
Portland cement	1.0	1.35	1.74	1.04
	2.0	2.15	0.63	0.81
	3.0	0.46	0.45	1.08
Portland cement + Pozzolith	P.c. 1.0 P. 0.1	1.35	0.59	0.67
	3.0 0.2	0.56		0.74
Portland cement + Darad 21	P.c. 1.0 D. 21 0.1	1.41		0.82
	2.0 1.5	1.08	0.76	0.14
	3.0 0.2	0.61		1.10
	5.0 1.0	0.59	0.47	0.36

Table V. Summary: effect of aggregants on frost heave (miniature specimens).

Additive		*Heave ratio**		
Type	*%*	*Boston blue clay*	*New Hampshire silt*	*Fort Belvoir sandy clay*
Flocgel	0.01	0.72	1.01	0.83
	0.05	1.16	0.72	0.61
	0.10	0.70	0.44	0.55
	0.10	0.61	0.48	0.55
CRD-197 soil conditioner	0.01		0.93	0.49
	0.05		0.88	0.50
	0.10	1.32	1.32, 1.39	0.58, 0.62
	0.50	2.27	2.31	0.74, 0.50
	1.00	1.87	2.91	0.07
Guartec	0.05	1.71	7.80	0.57
	0.10	1.36	2.70	0.75
	0.50	1.02	0.39	0.61
	1.00	1.16	0.53	0.20
Krilium #6 soil conditioner	0.01	1.94	1.35	0.69
	0.05	1.90	1.36	0.59
	0.10	1.79	0.96	0.54
	0.50	1.07	0.11	0.38
Agrilon	0.01	1.82	0.79	0.70
	0.05	2.08	0.83	0.69
	0.10	1.62	0.82	0.69
	0.50	0.80	0.45	0.32
Copolymer of styrene and methosulfate	0.10	0.71	0.03	0.76
	0.50	1.43	0.14	1.42
	1.00	1.79	0.30	0.87
PVA (Polyvinyl alcohol)	0.01	2.46	1.08	
	0.05	2.36	0.98	0.71
	0.10	2.24	0.93	0.44
	0.50	1.17	1.76	0.57
	1.00		0.78	0.50

* Heave ratio = (avg rate of heave of treated soil)/(avg rate of heave of untreated soil).

The data show neither general significant modification of frost susceptibility nor increase of effectiveness with increase in concentration. These results suggest that the treatment level was too low to obtain beneficial effects from plugging soil voids.

Portland cement. Table IV, results of tests on fine-grained soils treated with portland cement, indicates cement is not a promising frost heave modifier. The data show that more than 5% cement is required to reduce frost heave significantly and that cement plus a dispersant is more effective than cement alone. However, a treatment of cement plus dispersant is not as effective as a treatment of dispersant without cement. For example, 1% dispersant (Daxad 21) reduced the heave ratio of Fort Belvoir sandy clay to 0.10 (see Table IX) compared to 0.36 for the specimen with 1% Daxad 21 plus 5% cement (Table IV). The cement apparently had an adverse effect on the dispersant.

Limited tests run on standard-size specimens of a clayey gravelly sand (Appendix Table AIII) treated with portland cement and Daxad 21 also showed only modest improvements effected by this type of treatment.

Aggregants. Two aggregant types were studied: polymers and polyvalent cations. Tables V and VI present the results on seven widely differing polymeric aggregants. From these data the following observations can be made:

Table VI. Summary: effect of an aggregant on frost heave (standard-size specimens).

Soil: Name	Soil: Percent passing 0.02 mm	Heave ratio† by % concentration* of Agrilon: 0.01	0.05	0.10	0.50
Loring silty sandy gravel	4.0	1.56	0.89	1.11	
	6.8	0.73	0.59	0.31	
	12	0.69	0.53	0.40	
New Hampshire clayey silt	62-73		0.18	0.20	
			0.92	1.86	
Fort Belvoir sandy clay	49			0.77	0.53
				0.88	0.59

* % based on dry soil weight.

† Heave ratio (avg rate of heave of treated soil)/(avg rate of heave of untreated soil).

Table VII. Summary: effect of cations on frost heave (miniature specimens).

Soil	Heave ratio by type of cation tested: Iron $FeCl_3$	Iron $Fe_2(SO_4)_3$	Lead $PbAc_2$	Barium $BaAc_2$	Potassium KCl	Mercury $HgCl_2$
Fort Belvoir sandy clay	0.29		0.12			0.50
Boston blue clay	1.49 0.20	0.57	1.56	1.09	1.10	0.70
New Hampshire silt	0.48		0.37			0.77
Fairbanks silt	0.88	0.88		1.93	0.65	
Niagara Falls clay	0.02			0.65	1.39	
Portsmouth sand	0.29	2.56		3.22	2.13	
Loring till	0.05	0.44		1.20	0.52	
Fargo clay	1.05	0.29		4.62	1.35	
WASHO clay	0.12	1.32		0.97	0.62	

1) The polymers are generally not very effective.

2) The effect of concentration of polymer can be large and unpredictable.

3) The polymers can be detrimental.

4) The effectiveness of the polymers depends considerably on the type of soil treated.

The unpredictable behavior of polymeric aggregants, especially the influence of aggregant concentration, is a discouraging fact that has been observed in other studies. As a matter of fact, when applied in large quantities many of these aggregants behave as dispersants. Their modest effectiveness, the importance of their concentration and their high cost combine to make the polymer aggregants unpromising as frost heave modifiers.

Table VIII. Summary: effect of waterproofers on frost heave (miniature specimens).

Additive		Heave ratio		
Type	%	Boston blue clay	New Hampshire silt	Fort Belvoir sandy clay
SC-50	0.01	1.14	0.85	0.50
	0.05	1.06	0.51	0.37
	0.10	0.34, 0.48	0.60, 0.41	0.39, 0.47
	0.50	0.07, 0.06	0.43	0.06, 0.26
	1.00	0.05, 0.14	0.27	0.05, 0.01
Sodium methyl ethyl propyl siliconate	0.01			0.74
	0.05	0.70	0.78	0.65
	0.10	0.62	0.66	0.39
	0.50	0.14	0.53	0.12
	1.00	0.13	0.23	
Potassium phenyl siliconate	0.01			0.69
	0.05	0.53	1.20	0.73
	0.10	0.90	1.58	0.70
	0.50	0.37	0.45	0.60
	1.00	0.25	0.76	
Triton K-60	0.10	1.02	0.43	0.74
	0.50	1.36	0.55	0.53
	1.00	1.19	0.29	0.71
Volan	0.01	0.85	0.51	0.61
	0.05	0.81		
	0.10	0.68, 0.70	0.31, 1.73	0.27, 0.66
	0.50	0.00, 0.41	0.21	0.24, 0.23
	1.00	0.20, 0.09	0.17	0.11, 0.10

Table VII presents the effects of six polyvalent cations on the frost heave of nine soils. Lead and mercury ions were experimented with, not so much as aggregants but as waterproofers since they are non-hydratable ions. No treatment levels are given in Table VII; enough of each salt was added to saturate the ion-exchange capacity of the soil with the salt's cations. Since all of the soils listed in Table VII have low exchange capacities, the required treatments were low, always less than 0.5%. After treatment the soils were washed and dried.

Some reaction in addition to ion exchange and ion fixation took place since ferric sulfate was inferior to ferric chloride. The reasons for this difference were suggested earlier under *Theoretical Considerations* where it was noted that ferric hydroxide, a potential cement agent, could be formed from ferric chloride. In future tests on cations, consideration should be given the accompanying anions and the amount of salt used.

The main disadvantage to the use of cations, such as ferric iron, is the probable need for drying the treated soil. The importance of drying will be investigated. Certainly the results on half of the soils treated with ferric chloride are most encouraging. Other studies (Massachusetts Institute of Technology Soil Stabilization Laboratory) have demonstrated the additional encouraging fact that ferric chloride has a beneficial effect on the strength characteristics of soil.

Waterproofers. Table VIII presents the results of tests to evaluate 18 waterproofers as frost-heave modifiers. All soils were dried after treatment and, in some instances, were dried before the chemical was added. These necessary preparations and cure conditions are, of course, an undesirable feature of waterproofers.

The results in Table VIII show that the effects varied from very beneficial to detrimental, with the majority being beneficial. As with polymeric aggregants, the effects of the waterproofers are not predictable, e.g. Primene 81-R was beneficial with New Hampshire silt but

Table VIII (cont'd). Summary: effect of waterproofers on frost heave (miniature specimens).

Additive		Heave ratio*		
Type	%	Boston blue clay	New Hampshire silt	Fort Belvoir sandy clay
Quilon	0.01		1.30	0.55
	0.05	0.80		
	0.10	0.97, 0.99	0.33, 1.37	0.40, 0.68
	0.50	0.56, 0.97	0.48	0.38, 0.36
	1.00	0.65	0.02, 1.07	0.18, 0.15
Hyamine 1622	0.10	1.19	0.69	0.92
	0.50	1.54	0.41	0.42
	1.00	1.48	0.36	0.60
Hyamine 2389	0.10	1.24	0.92	0.59
	0.50	1.40	0.39	0.41
	1.00	1.44	0.28	0.42
Triethylene tetramine	0.10	1.10	0.64	0.41
	0.50	1.36	0.28	0.42
	1.00	1.23	0.20	0.51
Hexamethylene diamine	0.01		0.70	
	0.05		0.99	
	0.10	1.18	0.02, 1.21	0.49, 1.12
	0.50	2.38	0.36	0.38, 0.77
	1.00	2.33	0.33	0.16, 0.51
Di-N-Butylamine	0.05			0.57
	0.10	2.14	0.78	0.44
	0.50	0.71	0.45	0.31, 0.72
	1.00	0.80	0.39	0.12, 0.25
Primene 81-R	0.01		1.20	
	0.05		0.72	
	0.10	2.51	0.84, 0.39	1.55
	0.50	3.54	0.19, 0.16, 0.63	1.15
	1.00	3.91	0.15, 0.20	1.32
Carbowax Peg 200	0.01		-	0.55
	0.05			1.00
	0.10	1.59	0.55	0.78, 0.92
	0.50	0.70	0.32	0.18, 0.21
	1.00	0.63	0.37	0.31
Carbowax Peg 6000	0.01			0.57
	0.05			0.62
	0.10	1.34, 0.95	0.49	0.88, 0.89
	0.50	1.23, 0.90	0.53	0.28
	1.00	0.31, 0.40	0.21	0.39
Arquad 2 HT	0.10	2.46	0.84	1.06
Armeen 18D	0.10	2.53	1.10	1.25
Diethanol Rosin Amine D Acetate	0.10	1.02		
	0.50	1.30		
	1.00	1.48		
Monoethanol Rosin Amine D Acetate	0.10	0.75		
	0.50	1.44		
	1.00	2.80		

* Heave ratio (avg rate of heave of treated soil)/(avg rate of heave of untreated soil).

detrimental with Boston blue clay. As would be expected, the more waterproofer used, the better the results; generally, marked benefits were obtained only with treatments of 0.5% and more.

The high cost of waterproofers and the need to dry the treated soils dim the prospects of these materials as frost heave modifiers, even though they can be extremely effective. However, they might have limited uses in practice.

Dispersants. Tables IX and X, the results of freezing tests on miniature and standard-size specimens treated with various dispersants, indicate that dispersants can be very effective as frost heave modifiers. The data show several important and favorable facts:

1) The great majority of dispersants were effective at and above treatment levels as low as 0.1%.
2) In general, the higher the treatment level the better the results, but improvement past 0.5% was slight.
3) The three polyphosphate dispersants appear to be the most efficacious frost heave modifiers.

Figure 3 is a plot of heave ratio and additive concentration for the three polyphosphates tested. The sample molding conditions were intentionally varied for these tests from very dry to very wet as compared with optimum moisture. No trend of effectiveness varying with molding moisture could be detected; in fact, Figure 3 shows little variation in heave at any given additive concentration.

Dispersants are particularly promising as soil additives since they are effective in low concentrations, are relatively cheap, have beneficial effects on other soil properties (Lambe, 1954), are comparatively easy to incorporate, react instantaneously, and require no pre- or post-treatment curing (Linell and Kaplar, 1959). Because of the favorable results (Tables IX, X) further tests, described below, were conducted.

A great many of the granular soils are unacceptable for fill material in the frost zone, not because of their strength characteristics under "normal" conditions, but because of their frost behavior. Even though a frost-susceptible sand or gravel ("dirty gravel") may have a very high

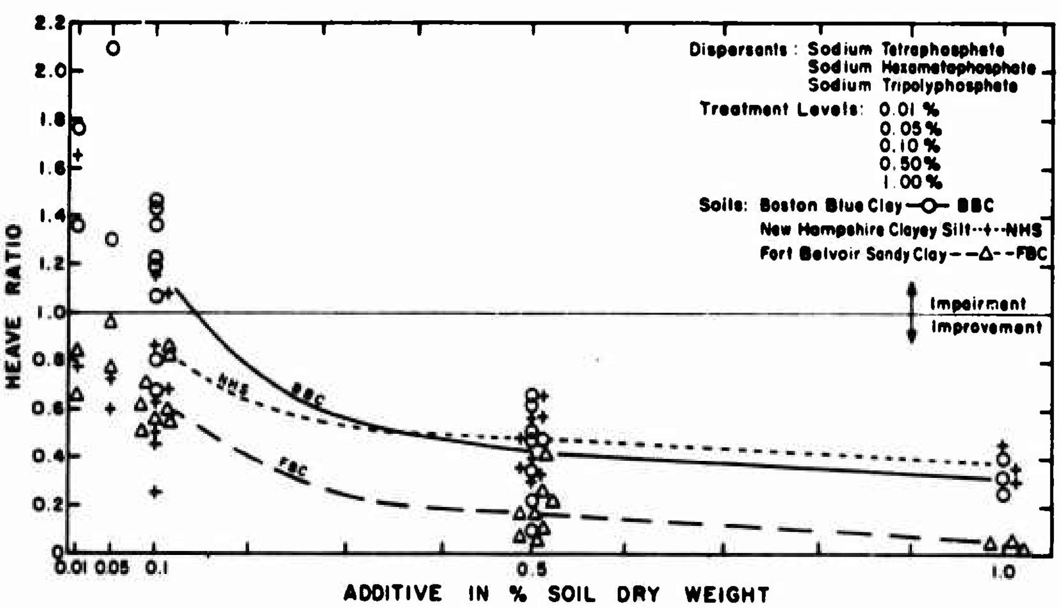


Figure 3. Effect of three polyphosphate dispersants on frost heave of miniature specimens.

Table IX. Summary: effect of dispersants on frost heave (miniature specimens).

Additive Type	%	Heave ratio* Boston blue clay	New Hampshire silt	Fort Belvoir sandy clay
Quadrafos (Sodium tetraphosphate)	0.01	1.77	0.79	0.65
	0.05	2.10	0.60	0.77
	0.10	1.42, 0.69	0.44, 1.09	0.53, 0.57
		1.22, 1.07	0.26, 1.17	0.84, 0.62
		1.43, 0.80	0.68, 0.85	0.83, 0.53
	0.50	0.67, 0.66	0.54, 0.32	0.11, 0.18
		0.10, 0.51	0.39, 0.64	0.08, 0.26
		0.49, 0.21	0.31, 0.36	0.18, 0.22
	1.00	0.40	0.36	0.06
Sodium hexameta-phosphate	0.01	1.36	1.64	0.82
	0.05	1.50	0.72	0.96
	0.10	1.37	0.50	0.70
	0.50	0.37	0.58	0.42
	1.00	0.25	0.29	0.06
Sodium tri-polyphosphate	0.10	1.20	0.63	0.51
	0.50	0.47	0.48	0.09
	1.00	0.32	0.46	0.00
Versenate chelate	0.05	1.30	0.94	0.72
	0.10	1.06	0.89	0.18
	0.50	0.71	0.79	0.49
Tanol 731	0.01	1.73	1.00	0.71
	0.05	1.75	0.99	0.53
	0.10	1.45	0.55	0.39
	0.50	0.48	0.45	0.11
	1.00	0.39	0.38	0.00
Daxad 11	0.01		1.11	0.69
	0.05		0.83	0.68
	0.10		0.74	0.62
	0.50		0.15	0.20
	1.00		0.33	0.05, 0.09
Daxad 21	0.01	1.69		
	0.05	1.51, 1.00	3.38	0.71
	0.10	1.63, 0.82	0.85	0.62
	0.50	0.97, 1.05	0.91	0.31
	1.00	0.68, 0.92	0.41	0.10
Marasperse N	0.05	1.63	0.50	0.81
	0.10	1.15	0.54	0.31
	0.50	1.41	0.42	0.08
Marasperse C	0.05	1.70	0.52	0.39
	0.10	2.17	3.12	0.67
	0.50	1.31	0.28	1.07
Lignosol	0.05	0.91	0.98	0.73
	0.10	0.71	1.18	0.42
	0.50	0.45	1.55	0.18
	1.00	0.57	0.57	0.18

* Heave ratio = (avg rate of heave of treated soil)/(avg rate of heave of untreated soil).

Table X. Summary: effect of a dispersant on frost heave (standard-size specimens).

Soil	*Percent passing 0.02 mm*	*Heave ratio by % concentration* of Quadrafos*			
		0.10	*0.30*	*0.50*	*1.00*
Loring clayey sandy gravel	30		0.16		
Portsmouth sandy clay	33	0.85			
New Hampshire clayey silt	62-73	0.18, 0.68		0.15, 0.43	
Fort Belvoir sandy clay	43-49		0.18, 0.24 0.18, 0.46		0.06, 0.06

* % based on dry soil weight.

California Bearing Ratio value after soaking, it should not be used as a pavement base or foundation fill in the freezing zone because of frost heaving and resultant weakening. A treatment that could make these otherwise excellent materials non-frost-susceptible would be most useful.

To test the effectiveness of a chemical dispersant as a modifier of the frost heave of dirty gravels, 11 silty sands and gravels were treated with 0.3% tetrasodium pyrophosphate (TSPP) and subjected to controlled laboratory freezing tests. The results of these tests are presented in detail in Table AIV, summarized in Table XI, and plotted in Figure 4. The results show that the TSPP

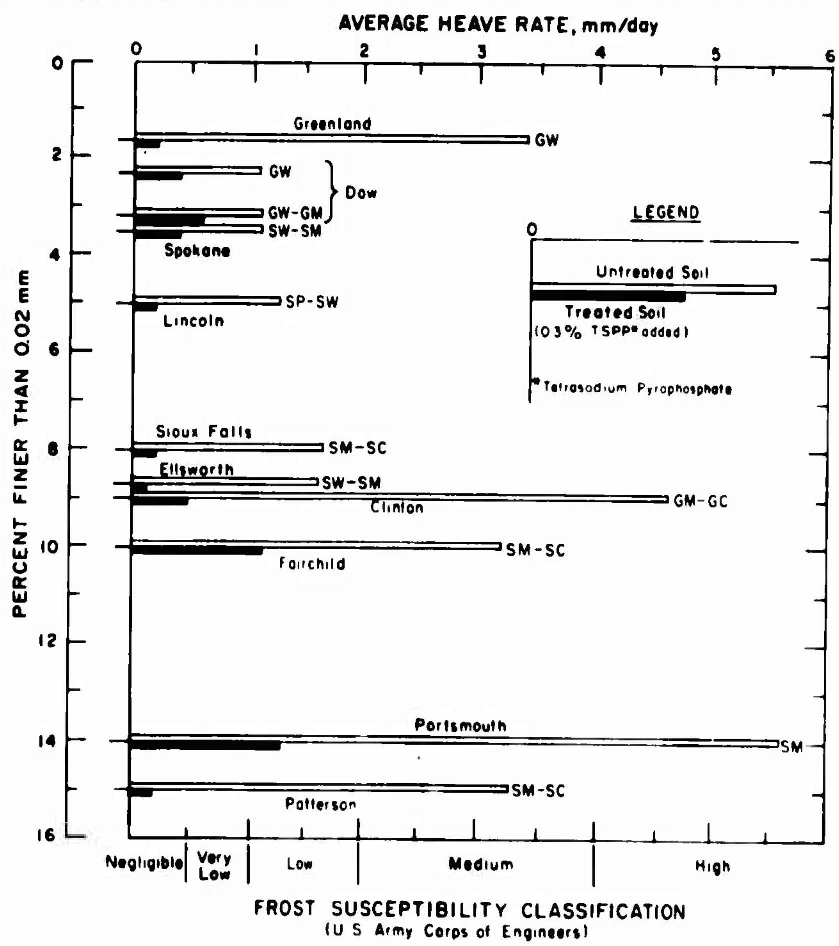


Figure 4. Freezing test on dirty gravels. 6 in. diam × 6 in. long cylindrical specimens (open system).

Table XI. Summary of freezing tests on dirty gravels treated with tetrasodium pyrophosphate (standard-size specimens – open system).

Soil		Untreated soil				Soil treated with 0.3% TSPP				
Description	Symbol (Unified soil class. system)	Percent passing 0.02 mm	Molding water (%)	Dry unit weight (lb/cu ft)	Average rate of heave (mm/day)	Percent passing 0.02 mm	Molding water (%)	Dry unit weight (lb/cu ft)	Average rate of heave (mm/day)	Heave ratio
Dow sandy gravel	GW	2.4	5.0	131	1.1	2.4	5.0	131	0.4	0.36
Greenland sandy gravel	GW	1.7	5.0	140	3.4	1.7	3.0	143	0.2	0.06
Dow silty sandy gravel	GW-GM	3.2	5.0	134	1.1	3.2	5.0	134	0.6	0.55
Clinton silty clayey gravel	GM-GC	15	9.0	129	4.6	9.0	5.0	129	0.5	0.11
Ellsworth silty gravelly sand	SW-SM	8.7	6.0	137	1.7	8.7	5.0	137	0.1	0.06
Spokane gravelly sand	SW-SM	3.5	6.0	128	1.1	3.5	5.0	128	0.4	0.36
Lincoln gravelly sand	SP-SM	5.0	7.0	132	1.2	5.0	4.8	134	0.2	0.17
Fairchild silty clayey sand	SM-SC	9.5	4.5	131	3.2	10.0	6.3	131	1.1	0.34
Portsmouth silty gravelly sand	SM	14	8.5	127	5.6	14	5.0	130	1.3	0.23
Sioux Falls silty clayey gravelly sand	SM-SC	9.0	4.0	131	1.7	8.0	11.1	128	0.2	0.12
Patterson silty clayey gravelly sand	SM-SC	15	5.0	135	3.3	15	4.7	137	0.2	0.06

Data from Table AIV.

reduced the rate of frost heave in all 11 soils. The minimum reduction was to 0.5 of the untreated value, the maximum to essentially zero, and the average reduction was to 0.2 of the untreated value. Figure 4 shows that 8 of the 11 soils were made to fall within the Corps of Engineers Frost Susceptibility Classification of *Negligible*, while the other 3 were in the categories *Low* or *Very low*.

In Figure 4 the results of freezing tests were plotted as a function of "% finer than 0.02 mm" to see if the effectiveness of the dispersant was a function of fines content. The main relationship apparent is that the greater the rate of heave of the natural soil, the greater the reduction caused by the dispersant; no relation between fines content and chemical performance is apparent.

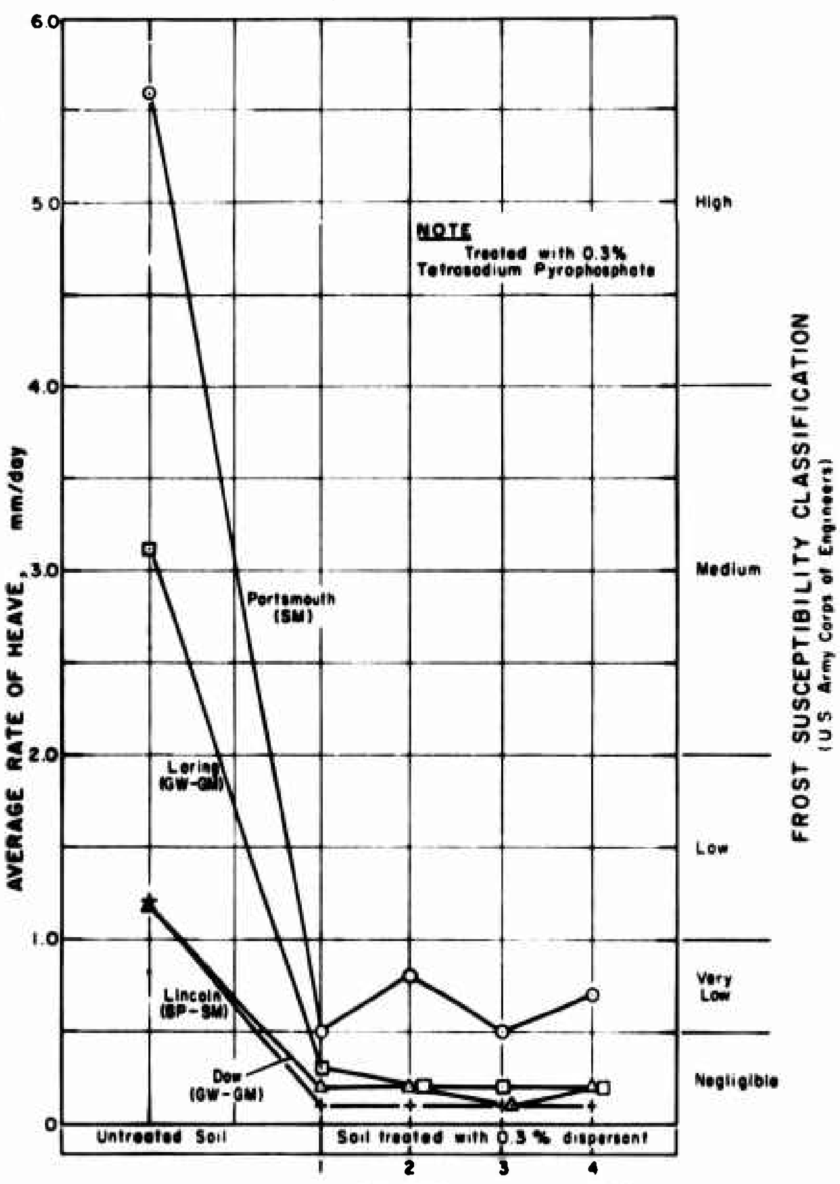


Figure 5. Freeze-thaw cycles on dirty gravels.

The reason why dispersion is so effective in dirty gravels is not known, but it may be the following: Since the overall structure of these soils is controlled by the gravel-size particles, dispersion has little effect on the overall density (this fact can be observed from a comparison of the densities of untreated and treated samples, Table XI). Disaggregating the fines permits them to pack into a smaller space, thereby making the voids among gravel particles larger. In fact, the dispersed fines can be moved by pore water. Tests which have shown that dispersants can increase the permeability of dirty gravels support the hypothesis of "cleaning" the soil.

For an additive to be of practical value, it must, in addition to being an effective frost-heave modifier, have reasonable permanence. As previously mentioned, the temporary effectiveness of salt in reducing the freezing point of soil void water is, for example, a major drawback. How permanent then are the other treatments, especially the very promising dispersant treatments described here?

Theoretical considerations suggest that when dispersants alter the structure of the entire soil mass, cycles of freezing and thawing may undo some of the improvements in structure. The effectiveness of a dispersant on a clay may well be gradually decreased over a number of years. On the other hand, where the structure benefits are limited to a small proportion of the particles, freeze-thaw cycles probably have little, if any, influence.

A series of tests was conducted on standard-size specimens of four treated dirty gravels to ascertain the effect of freeze-thaw cycles. The results, presented in Table AV and summarized in Figure 5, show no loss of dispersant effectiveness during four cycles of freeze-thaw (i.e., the duration of the tests). Figure 5 also illustrates the pronounced reduction of frost susceptibility that can be obtained from dispersants.

The indicated permanence of dispersant treatment (Fig. 5) is substantiated by the results obtained in the field test described below.

Field test: Effect of a dispersant on frost heave

To see if the laboratory tests were indeed indicative of field conditions, a small-scale field test was conducted at Loring Air Force Base, Limestone, Maine. Three test sections, 4 ft × 4 ft × 1 ft deep, were prepared at a site where the water table was about 20 ft below ground surface. One section was of undisturbed soil; another of soil which had been remolded but given no chemical treatment; and a third section of soil which was hand-mixed with 0.3% sodium tetraphosphate (Quadrafos, a dispersant). The soil was a clayey sandy gravel (i.e. glacial till) with a liquid limit of 21%, a plasticity index of 6%, and about 30%, by weight, of its particles finer than 0.02 mm. Laboratory tests (Table AIV) showed that the 0.3% treatment resulted in a heave ratio of 0.16 associated with a reduction in the average rate of heave from 3.2 to 0.5 mm per day.

The sections were prepared on 8 December 1953. During two frost-melting periods, the frost lines, as located in test pits, were as follows:

Penetration of 32F isotherm (in inches)

Date	*Undisturbed untreated section*	*Remolded untreated section*	*Chemically treated section*
16-19 March 1954	3	4	4
2-4 April 1955	20	12	17

The greater penetration of the 32F isotherm in the chemically treated section (17 in.) as compared to the remolded, untreated section (12 in.) for the winter period ending in April 1955 is attributed to the lesser quantity of latent heat released because of reduced heaving and thus a slightly greater penetration. Also a soil of greater density possesses a higher thermal conductivity which may account for some of the difference observed.

Some of the results are shown in Figures 6 and 7. Figure 6 presents ground surface elevation as a function of time: it shows the following:

Heave (in feet)

Date	*Undisturbed untreated section*	*Remolded untreated section*	*Chemically treated section*
19 March 1954	0.28	0.35	0.14
5 April 1954	0.39	0.47	0.18
2 April 1955	0.50	0.56	0.28

In comparison with either of the untreated sections, the dispersant caused a significant reduction in heave. Most important is the fact that the dispersant was effective the second year, i.e. during the second freeze-thaw cycle. The heave ratios in the field test, approximately 0.5, compare well with the heave ratio from the laboratory tests, 0.2, when the conditions at the test site are considered, as follows:

An explanation of why the results of chemical treatment did not show up better in the field test is furnished by Figure 7. This figure shows two things: 1) the treated and untreated (remolded) soil sections were placed at very low dry unit weights of 100 and 92 lb/cu ft, respectively, caused by rain during construction (the Corps of Engineers Modified AASHO Density Test*

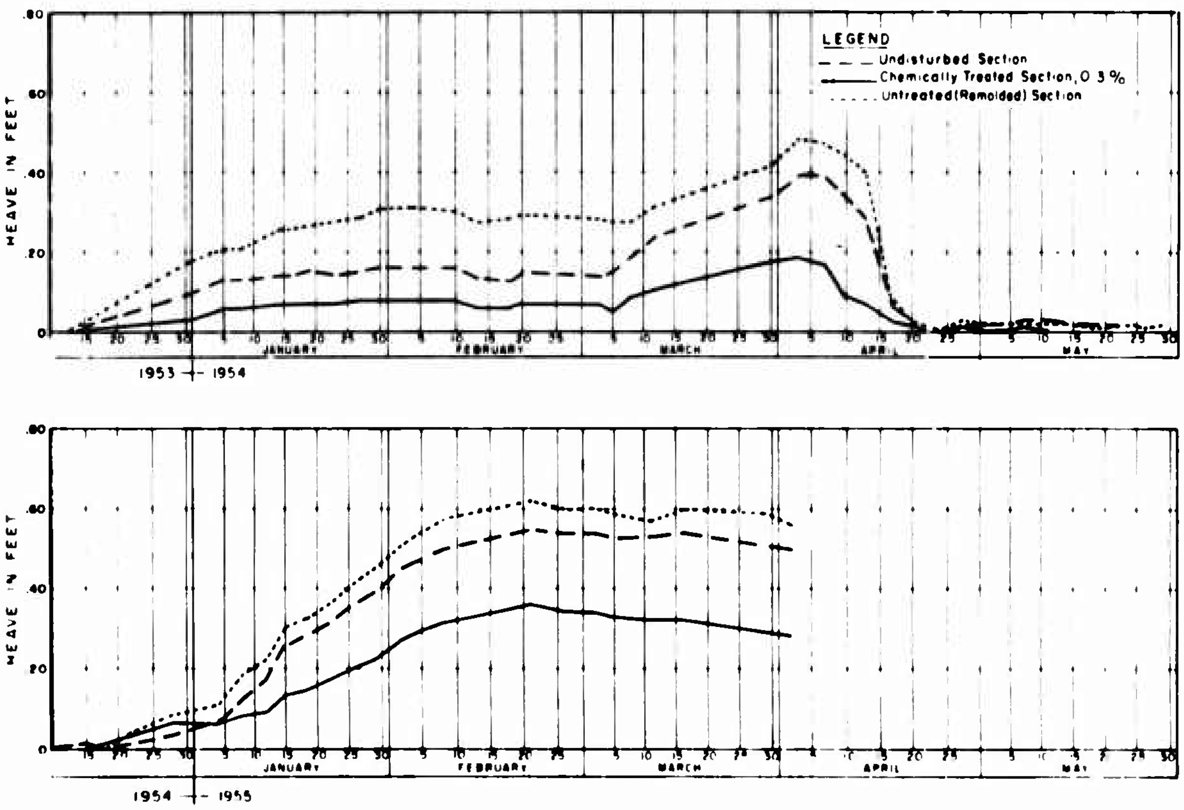
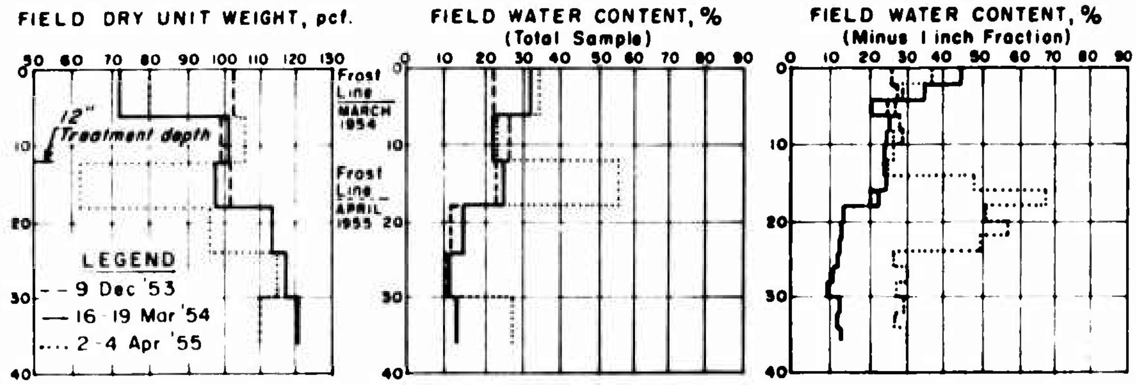
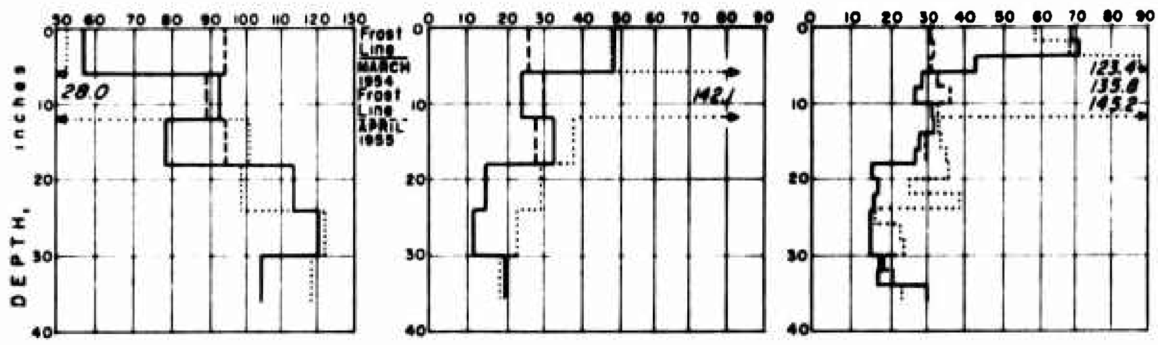


Figure 6. Sodium tetraphosphate admixture test section – heave vs time.

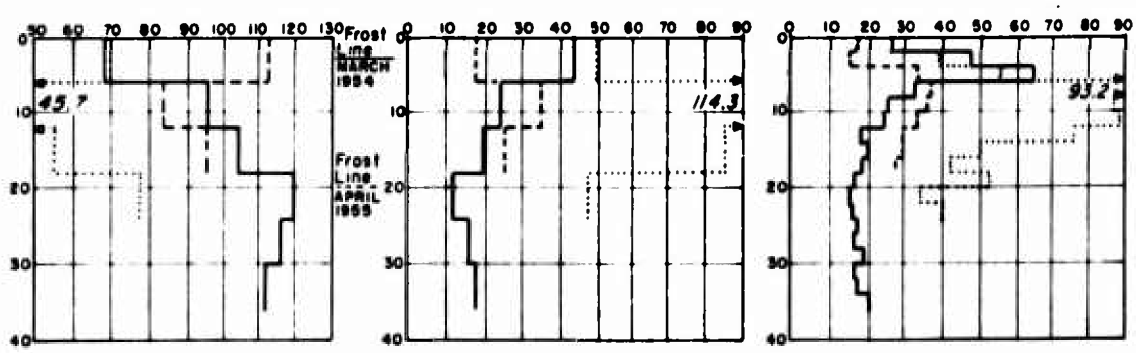
* Corps of Engineers Modified AASHO Density Test is made by compacting soil in a 6-in.-diam cylinder, 1/10 cu ft in volume, using five layers, 10-lb tamper and 18-in. drop, 55 blows per layer.



a. *Chemically treated section.*



b. *Untreated (remolded) section.*



c. *Undisturbed section.*

Figure 7. Sodium tetraphosphate admixture test section – density and water content vs depth.

maximum is 137 lb/cu ft); and 2) most of the dry unit weight loss and moisture increase in the treated section occurred below the treated zone. In other words, a large percentage of the heave in the treated section occurred in the untreated soil underlying the treated soil. In fact, most of the 1955 heave in the treated section came from the untreated soil. Figure 7 shows that the dry unit weight loss during the 1955 thaw for the treated section was 22 lb/cu ft or 22% for the top 6 in. of treated soil while for the underlying untreated 6 in. of soil in the frost zone the dry unit weight loss was 40 lb/cu ft.

This limited field test produced these encouraging results:

1) The laboratory test was indicative of field performance.

Table XII. Overall evaluation of additives as frost heave modifiers.

Additive	*Effectiveness* as indicated by laboratory test*	*Requirements for soil-additive reaction*	*Required additive concentration*	*Additive cost per pound*	*Effect on soil properties other than frost action*	*Field use*	*Comments*	*Evaluation* as frost heave modifier*
Void fillers and cement								
a. In situ polymerization (Calcium acrylate)	Excellent	Polymerization marked function of temperature	5%	50¢	Beneficial increase in strength and density, decrease in permeability	Difficult to control polymerization	Intended for emergency use	Poor
b. Resins and asphalt	Promising	Drying after treatment – some require soil be pre-dried	1%	1 to 15¢	Beneficial	Other than cure requirements, no special problems		Promising
c. Portland cement	Promising (with additives to cement)	Cure period for cement hydration	4%	1 to 2¢ (cement) 6 to 12¢ (additives)	Beneficial	No special problems		Slightly promising
Aggregants								
a. Polymers	Poor to slightly promising	None	< 1%	12¢ to $1.00	Beneficial	Moderate mixing and processing problems expected	Effectiveness unpredictable and is a function of concentration	Poor to slightly promising
b. Cations	Excellent	None for some, drying after treatment for others	<0.5%	2¢ and up	Beneficial	No special problems expected		Very promising
Dispersants	Excellent	None	<1%	5¢ to $1.00	Beneficial	No special problems		Very promising
Waterproofers	Excellent	Drying after treatment	<0.5%	25¢ to $2.00	Beneficial	Probable need for high degree of drying		Promising

* Adjective rating scale: poor, slightly promising, promising, very promising, excellent.

2. The chemical dispersant was effective in reducing frost heave, density loss and moisture gain in the frost zone.
3. The effectiveness of the chemical was not impaired by a freeze-thaw cycle.

In future field tests, a site with a higher water table should be selected and the treatment should be extended below the frost zone.

SUMMARY AND CONCLUSIONS

Summary

This report describes a search for additives to reduce the frost susceptibility of soil; the 3-year search involved over 1000 freezing tests using 25 soils and 52 additives. The additives tried were chosen because of various theoretical reasons why each might reduce the moisture migration necessary for ice-lens formation. The additives were divided into four groups according to their action in soil: 1) void fillers and cements, 2) aggregants, 3) waterproofers, and 4) dispersants.

Conclusions

Table XII gives an overall evaluation of the additives studied. This evaluation considers their effectiveness as frost heave modifiers as indicated by the freezing tests described here, their cost, and the ease with which they can be used in the field. Any evaluation of the additives must consider the last two practical items, even though the tests reported primarily measured their effectiveness as frost heave modifiers. The evaluation in Table XII is based on judgment as well as on quantitative test results.

The salts of polyvalent cations – especially ferric chloride – and the dispersants appear to be very promising as additives for reducing the frost susceptibility of soil at low cost. Some of the resins and waterproofers show enough promise to warrant further laboratory testing.

A small-scale field test showed a laboratory-proved dispersant to be effective under field conditions; measurements made during the second freezing cycle showed no reduction in the potency of the dispersant treatment. Four freeze-thaw cycles on four dispersant-treated soils tested in the laboratory also had no adverse effects.

While the primary objective of the test program was to screen additives, enough different soils were used to permit some important, if tentative, observations concerning effect of soil type. Well-graded soils with some coarse particles – gravel or large sand size – respond to treatment best. Uniform silts and moderately plastic clays are the least responsive. The most promising use of additives is in treatment of well-graded soils with coarse particles whose mass structure is determined by the large particles. Such dirty gravels, sandy clays, and silty sands can often be made essentially non-frost-heaving with additives at an additive cost of about $1.00/cu yd of soil treated. The overall cost of treatment would depend, of course, on such factors as the type and condition of the particular soil to be treated. Additives could possibly be incorporated with base and subbase soils with little difficulty since those soils are usually obtained from borrow areas, placed in layers, and worked before compaction. The soils could therefore be treated with little additional processing.

More field testing is required before the dispersants and other additives can be completely evaluated. Further, even though the dispersants appear to be effective in many frost-susceptible soils, the characteristics of treated specimens of the soil in question should be checked by laboratory freezing tests before dispersants are used in the field.

RECOMMENDATIONS

The theoretical and experimental studies summarized in this report have produced results which warrant a continued program of research. The following program is therefore recommended.

Laboratory investigation

Laboratory evaluation of promising additives should be continued. The tests described in this report have shown that a number of additives, especially dispersants and polyvalent cation salts, merit further laboratory evaluation. In addition, experiments should be continued with thus far untried additives which have been suggested by results on related chemicals. Tests to determine the effect of different cure conditions should also be performed. The program should include further tests on soils treated with portland cement, lime, and asphalt in order to permit a comparison of the effectiveness of any newly discovered frost-heave modifiers with conventional soil stabilizers.

It is also recommended that laboratory evaluation be made of the permanence of effectiveness of such promising additives as the dispersants and polyvalent cation salts in the face of water and bacterial attack.

Field test

Materials which laboratory testing shows to be effective should be field-tested. It is recommended that a small field test section using a frost-susceptible dirty gravel treated with a polyphosphate dispersant be constructed in a location where the winter climate is moderately severe in order to observe behavior under naturally occurring conditions. In such a test section, the treatment should extend over the entire depth of frost penetration or a non-frost-susceptible soil should underlie the treated base course, and the elevation of the water table should be rigidly controlled at the bottom of the base course to provide relatively easy access to water. Observations of frost heave, moisture migration, and deflections under load after thawing, over several freezing seasons,

in comparison with observations on an untreated test section, should demonstrate the effectiveness and permanence of treatment in the field.

It is recommended that the emphasis of this program be placed on soils which, except for frost susceptibility, would be satisfactory base course or subbase materials.

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APPENDIX A: FREEZING TEST DATA

ILLUSTRATIONS

TABLES

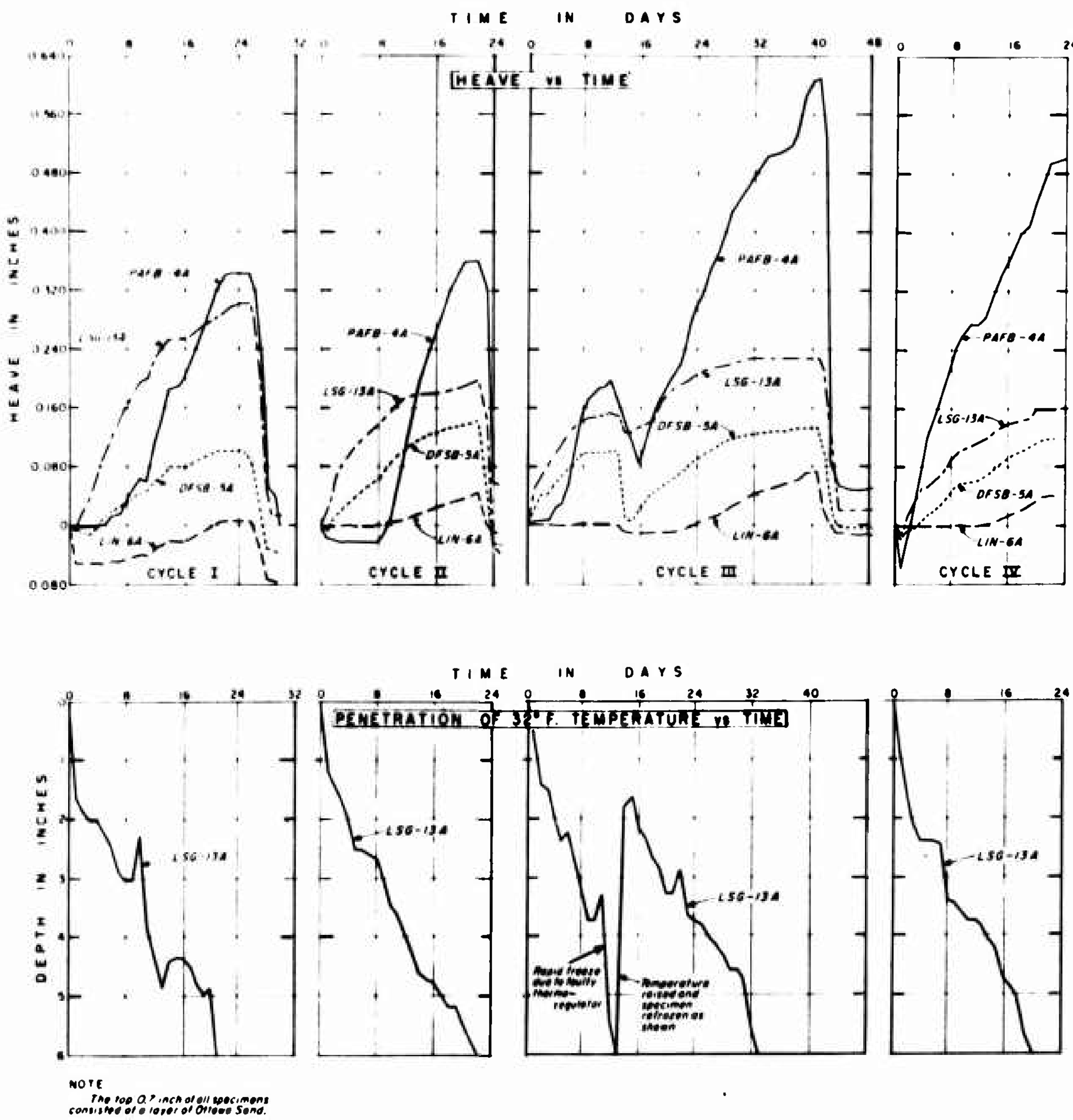

Figure A1. Alternate freeze-thaw tests with 0.3% TSPP treatment.

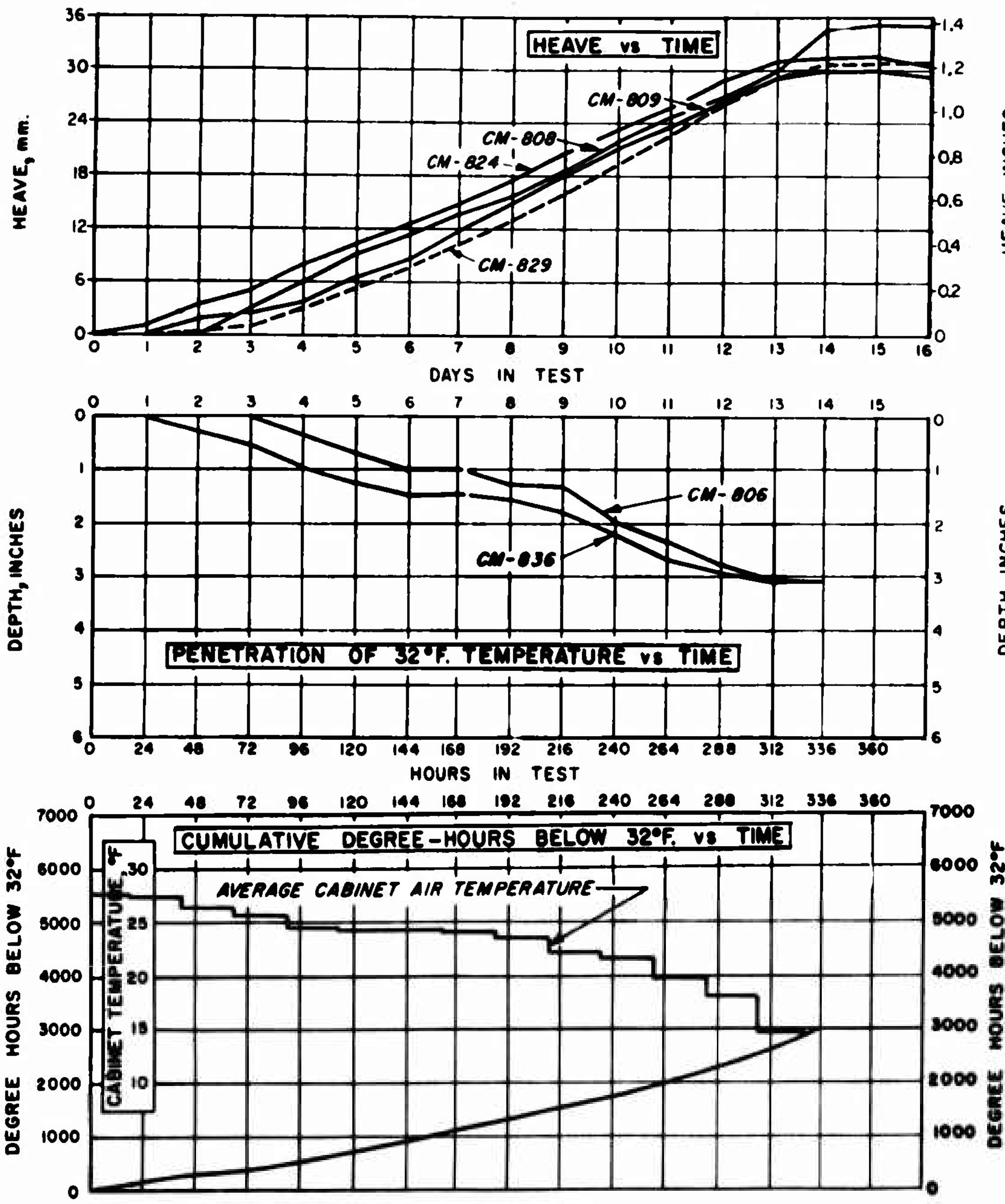

Figure A2. Typical curves of temperature and heave data for specimens CM-806, 808, 809, 824, 829 and 836.

Table AI. Freezing tests on untreated soils run in conjunction with freezing tests on treated miniature specimens (miniature specimens unless otherwise noted) (open system).

Specimen Number CM-	Tray No.	Soil	Dry Unit Weight pcf	Void Ratio	Percent Saturation at Start of Test	Average Water Content, %		Percent Heave	Average Rate of Heave mm/day		
						Before Freezing	After Freezing		Specimen	Average for Tray*	Average of All Tests To Date
735	55-1	Boston Blue CLAY Lab. Ser. No. 49-42	99.8	0.740	87.0	23.1	42.4	38.6	2.36		
743	55-1		95.6	0.813	83.3	24.4	44.9	41.2	2.39		
750	55-1		101.0	0.717	86.9	22.4	39.2	39.3	2.41		
756	55-1		99.2	0.748	76.1	20.5	39.9	35.0	2.38		
764	55-1		100.8	0.720	82.8	21.5	40.7	29.6	1.33	2.17	
770	55-2		103.1	0.681	93.5	22.9	35.0	30.8	2.01		
795	55-2		105.2	0.649	91.8	21.4	41.5	46.0	2.90	2.45	
1005	55-9		92.0	0.857	100	30.7	55.5	47.9	3.22	3.22	
951	55-10		104.9	0.653	87.8	20.6	33.1	38.3	1.78	1.78	
1032	55-11		109.1	0.590	72.8	15.4	31.7	26.7	1.09	1.09	
1073	56-1		104.0	0.668	94.7	22.7	38.5	42.1	2.33	2.33	1.82
1004	55-9	New Hampshire SILT Lab. Ser. No. 49-46	100.0	0.709	83.7	21.7	41.0	32.8	2.22		
1015	55-9		96.8	0.766	84.9	23.8	45.2	36.0	2.34	2.28	
1022	55-11		99.5	0.717	87.1	22.8	49.1	40.2	3.50	3.50	
1057	56-1		101.8	0.679	94.0	23.3	45.5	49.8	4.32	4.32	3.44
808	55-8	Fort Belvoir Sandy CLAY Lab. Ser. No. 49-66	108.7	0.550	93.7	19.1	33.4	34.7	2.87		
809	55-8		109.8	0.534	93.7	18.5	34.8	41.2	2.49		
824	55-8		108.8	0.548	96.8	19.7	33.9	40.8	2.52		
829	55-8		109.0	0.545	96.5	19.5	33.6	41.5	2.69		
834	55-8		108.4	0.554	94.1	19.3	35.6	48.2	3.01		
838	55-8		107.7	0.563	92.3	19.2	34.6	42.8	2.86	2.74	
1006	55-9		103.4	0.628	94.7	22.1	45.0	48.9	2.74	2.74	
1042	55-11		108.5	0.552	90.3	18.4	31.3	27.3	1.53	1.53	
1084	56-1		109.3	0.541	96.7	19.4	25.6	29.2	1.48	1.48	2.10
1007	55-9	Fairbanks SILT Lab. Ser. No. 49-63	99.2	0.685	90.1	23.0	41.7	39.8	2.13	2.13	-
956	55-10	Portsmouth SAND Lab. Ser. No. 49-55	112.8	0.509	83.0	15.5	25.3	26.7	1.44	1.44	-
961	55-10	Loring TILL Lab. Ser. No. 49-87	125.1	0.361	86.6	11.4	30.7	47.9	3.02	3.02	-
974	55-10	Fargo CLAY Lab. Ser. No. 50-58	98.5	0.748	79.1	21.4	21.0	4.2	0.17	0.17	-
979	55-10	WASHO CLAY Lab. Ser. No. 49-65	95.5	0.685	91.1	24.2	42.9	38.9	2.03	2.03	-
NF 3 **	-	Niagara Falls CLAY Lab. Ser. No. 49-78-3	92.6	0.874	100	31.4	40.4	35.7	1.50		
NF 4 **	-		94.0	0.845	100	30.4	-	36.8	1.50	1.50	-
791	55-2	Massachusetts Clayey SILT MIT Lab. No. M-21	117.6	0.464	88.1	14.8	32.6	43.1	2.97	2.97	-

NOTES: * Used as basis for heave ratios of additive-treated miniature specimens unless otherwise noted in Table A-2.

** Standard Size Specimen. Detailed water content, heave, and temperature data not available.

Table AII. Additive evaluation tests (miniature specimens) (open system).

Specimen Number	Tray Number	Soil	Additive	Percent	Dry Unit Weight pcf (1)	Void Ratio (1)	Percent Saturation at Start of Test	Avg. Water Content, % (2) Before Freezing	Avg. Water Content, % (2) After Freezing	Percent Heave (3)	Avg. Rate of Heave, mm/day	Heave Ratio (4)	Notes on Specimen Preparation
			RESIN-TYPE ADDITIVES										
CH- 767	55-2	Boston Blue CLAY	Vegetable Pitch 250	0.50	104.1	0.666	99.4	23.8	36.2	35.0	2.18	0.89	(a) Resin-type additives in Trays 55-2, 55-8, and 55-9 added to molding water and manually blended with dry soil until uniform mixture obtained. Mixture compacted, cured, saturated and frozen.
1029	55-11			0.50	109.4	0.584	86.1	18.1	26.3	18.3	0.50	0.46	
768	55-2			1.00	97.3	0.783	86.4	24.3	36.6	28.0	1.83	0.75	
1030	55-11			1.00	98.9	0.742	91.6	24.6	32.1	20.9	0.99	0.91	
769	55-2			3.00	93.4	0.856	85.7	26.4	37.8	25.7	1.65	0.67	
1031	55-11			3.00	94.1	0.830	81.8	24.6	37.1	26.7	1.20	1.10	
780	55-2		Tall Oil #50	0.50	98.1	0.767	87.4	24.1	39.9	32.4	1.78	0.73	(b) Resin-type additives in Tray 55-11 dissolved in gasoline and blended with dry soil; gasoline was evaporated, molding water was added, and the mixture manually blended for 9 minutes. Asphalt-emulsion-treated specimens were compacted immediately, cured saturated, and frozen. The other treated mixtures were allowed to equilibrate for a day before molding, curing, saturation, and freezing.
781	55-2			1.00	97.1	0.785	85.0	24.0	37.0	29.9	1.78	0.73	
782	55-2			3.00	93.7	0.851	76.2	23.3	36.6	27.0	1.57	0.64	
771	55-2		Vegetable Residue	0.50	97.0	0.788	86.6	24.5	35.2	27.8	1.78	0.73	
772	55-2			1.00	97.8	0.774	83.0	23.1	34.2	24.1	1.70	0.69	
773	55-2			3.00	97.5	0.779	89.3	25.1	38.9	32.8	2.16	0.88	
1033	55-11		Asphalt (Emulsion, 60% Solids)	0.50	97.6	0.769	86.3	24.0	30.4	14.3	0.59	0.54	
1034	55-11			1.00	95.1	0.831	92.6	27.0	36.1	21.5	1.07	0.98	
1035	55-11			3.00	93.5	0.803	95.9	28.5	33.4	23.8	0.47	0.43	
778	55-2		Polyamide Resin 100	0.10	87.8	0.975	78.7	27.6	45.6	28.0	1.45	0.59	(c) Curing after compaction, all specimens: 7 days at room temperature and humidity.
787	55-2			1.00	94.6	0.832	89.6	26.8	63.4	69.8	4.36	1.78	
802	55-2			3.00	84.2	1.060	81.6	29.3	77.3	70.7	4.50	1.84	
1019	55-11	New Hampshire SILT	Vegetable Pitch 250	0.50	97.6	0.751	85.4	23.4	43.5	40.1	2.88	0.82	
1020	55-11			1.00	96.4	0.760	78.7	22.0	48.5	50.5	3.53	1.01	
1021	55-11			3.00	90.6	0.852	84.9	26.9	57.7	57.9	4.44	1.27	
987	55-9		Tall Oil #50	0.50	97.1	0.759	85.1	23.6	33.6	19.0	1.10	0.48	
988	55-9			1.00	96.1	0.778	86.6	24.6	29.2	9.6	0.54	0.24	
989	55-9			3.00	98.8	0.729	78.2	20.9	27.8	10.0	0.57	0.25	
1001	55-9		Vegetable Residue	0.50	100.7	0.697	69.0	17.6	32.5	14.5	0.77	0.34	
1002	55-9			1.00	97.9	0.746	81.6	22.2	32.9	18.3	1.14	0.50	
1003	55-9			3.00	98.8	0.730	85.0	22.8	25.7	9.3	0.76	0.33	
1023	55-11		Asphalt (Emulsion, 60% Solids)	0.50	92.9	0.834	77.6	23.7	38.0	19.9	1.51	0.43	
1024	55-11			1.00	92.3	0.841	81.4	25.1	38.1	28.0	2.08	0.60	
1025	55-11			3.00	93.8	0.774	88.1	25.6	34.6	21.5	1.85	0.53	
1039	55-11	Fort Belvoir Sandy CLAY	Vegetable Pitch 250	0.50	103.5	0.630	96.4	22.2	26.9	21.9	1.12	0.73	
1040	55-11			1.00	103.1	0.622	95.8	22.2	27.3	15.8	0.84	0.55	
1041	55-11			3.00	100.3	0.648	81.7	20.0	28.6	16.7	0.61	0.40	
1043	55-11		Asphalt (Emulsion, 60% Solids)	0.50	102.9	0.630	94.1	22.0	25.7	13.2	0.49	0.32	
1044	55-11			1.00	101.4	0.642	89.9	21.6	26.9	14.5	0.52	0.34	
1045	55-11			3.00	102.0	0.609	85.9	19.9	24.7	13.8	0.79	0.52	
830	55-8		Polyamide Resin 100	0.10	103.0	0.634	99.3	23.3	40.1	42.5	2.83	1.03	
831	55-8			1.00	100.0	0.683	91.5	23.2	42.2	44.7	2.69	0.98	
832	55-8			3.00	95.7	0.760	87.1	24.5	47.2	48.6	3.35	1.22	
788	55-2	Massachusetts Clayey SILT	Vegetable Pitch 250	0.50	117.9	0.461	80.7	13.5	28.4	38.9	2.90	0.98	
789	55-2			1.00	119.6	0.440	82.8	13.2	33.7	48.9	3.40	1.14	
790	55-2			3.00	118.8	0.450	65.8	10.7	23.5	25.1	1.78	0.60	
792	55-2		Tall Oil #50	0.50	120.3	0.432	87.0	13.6	31.3	38.3	2.72	0.92	
793	55-2			1.00	119.1	0.445	93.0	15.0	28.3	35.7	2.49	0.84	
794	55-2			3.00	122.0	0.411	75.2	11.2	21.3	27.6	1.96	0.66	
783	55-2		Vegetable Residue	0.50	99.7	0.726	82.7	21.8	34.2	28.0	1.60	0.54	
784	55-2			1.00	120.3	0.431	90.4	14.1	30.2	39.2	2.82	0.95	
785	55-2			3.00	116.7	0.476	84.1	14.5	34.1	43.8	3.38	1.14	

General Note: See last sheet of this table for notes referred to by numbers in parentheses.

Table AII (cont'd).

Specimen Number	Tray Number	Soil	Additive	Percent	Dry Unit Weight pcf (1)	Void Ratio (1)	Percent Saturation at Start of Test	Avg. Water Content, % (2) Before Freezing	After Freezing	Percent Heave (3)	Avg. Rate of Heave, mm/day	Rate of Heave Ratio (4)	Notes on Specimen Preparation
			PORTLAND CEMENT & SECONDARY ADDITIVES										
CH-1065	56-1	Boston Blue CLAY	Portland Cement	1.00	105.1	0.645	89.9	21.5	44.7	50.8	3.15	1.35	(a) Cement and additives mixed with dry soil, molding water added, mixture manually blended for 9 minutes, and compacted.
1036	55-11			2.00	101.4	0.715	92.6	23.7	42.7	[illegible].3	2.34	2.15	
1066	56-1			3.00	99.8	0.744	91.5	24.4	35.3	21.2	1.08	0.46	
1067	56-1		Portland Cement plus Pozzolith	1.00 0.10	104.0	0.667	96.5	23.1	44.4	48.8	3.13	1.35	(b) Before saturation and freezing, specimens in Tray 55-11 cured 7 days at room temperature and humidity, those in Tray 56-1 cured 7 days at room temperature and 100% relative humidity.
1069	56-1		Portland Cement plus Pozzolith	3.00 0.20	102.1	0.704	92.8	23.3	35.1	23.5	1.29	0.56	
1068	56-1		Portland Cement plus Darex 21	1.00 0.10	103.4	0.677	97.7	23.8	47.1	56.3	3.29	1.41	
1037	55-11		Portland Cement plus Darex 21	2.00 1.50	100.8	0.725	90.0	23.4	35.6	22.2	1.17	1.08	
1070	56-1		Portland Cement plus Darex 21	3.00 0.20	103.7	0.677	98.0	23.8	32.1	25.4	1.42	0.61	
1038	55-11		Portland Cement plus Darex 21	5.00 1.00	97.4	0.791	87.8	24.8	33.2	19.0	0.64	0.59	
1055	56-1	New Hampshire SILT	Portland Cement	1.00	100.3	0.710	86.2	22.3	66.3	85.5	7.50	1.74	
1026	55-11			2.00	98.8	0.742	85.0	22.8	35.6	29.9	2.21	0.63	
1056	56-1			3.00	97.5	0.758	90.9	25.1	35.9	24.4	1.96	0.45	
1058	56-1		Portland Cement plus Pozzolith	1.00 0.10	101.4	0.686	98.6	24.7	42.4	40.5	2.55	0.59	
1027	55-11		Portland Cement plus Darex 21	2.00 1.50	98.6	0.745	76.2	20.6	31.3	22.2	2.64	0.76	
1028	55-11		Portland Cement plus Darex 21	5.00 1.00	100.2	0.730	82.1	21.6	28.9	17.4	.65	0.47	
1078	56-1	Fort Belvoir Sandy CLAY	Portland Cement	1.00	111.2	0.527	91.6	17.4	24.9	27.0	1.54	1.04	
1046	55-11			2.00	105.0	0.585	95.4	20.9	28.9	23.8	1.24	0.81	
1079	56-1			3.00	107.0	0.579	88.5	18.9	31.6	27.4	1.60	1.08	
1081	56-1		Portland Cement plus Pozzolith	1.00 0.10	112.6	0.501	100	18.5	21.3	10.3	0.99	0.67	
1083	56-1		Portland Cement plus Pozzolith	3.00 0.20	108.3	0.563	91.9	19.1	21.8	16.1	1.10	0.74	
1080	56-1		Portland Cement plus Darex 21	1.00 0.10	111.5	0.510	94.6	17.9	22.4	18.7	1.21	0.32	
1047	55-11		Portland Cement plus Darex 21	2.00 1.50	112.1	0.485	96.5	17.5	21.6	6.5	0.21	0.14	
1082	56-1		Portland Cement plus Darex 21	3.00 0.20	108.6	0.559	92.2	19.0	25.7	24.4	1.62	1.10	
1048	55-11		Portland Cement plus Darex 21	5.00 1.00	100.3	0.629	48.9	11.7	25.2	9.0	0.55	0.36	

General Note: See last sheet of this table for notes referred to by numbers in parentheses.

Table AII (cont'd).

Specimen Number	Tray Number	Soil	Additive	Percent	Dry Unit Weight pcf (1)	Void Ratio (1)	Percent Saturation at Start of Test	Avg. Water Content, % (2) Before Freezing	After Freezing	Percent Heave (3)	Avg. Rate of Heave mm/day	Rate of Heave Ratio (4)	Notes on Specimen Preparation
			AGGREGANTS										
936	55-9	New Hampshire SILT	Polyvinyl Alcohol (PVA)	0.01	95.9	0.784	86.5	24.8	44.5	38.9	2.46	1.98	a Aggregants added to molding water, manually blended with soil until uniform mixture obtained. Mixture compacted, saturated, and frozen.
940	55-9			1.00	94.4	0.811	83.7	26.5	35.6	21.9	1.78	0.79	
916	55-8	Fort Belvoir Sandy CLAY	Maleic Polymer (Krilium 6)	0.01	107.5	0.556	98.2	20.6	33.8	35.7	1.30	0.69	
917	55-8			0.05	108.9	0.548	95.2	19.3	28.4	23.4	1.03	0.59	
918	55-8			0.10	109.0	0.544	93.4	18.6	27.8	22.8	1.17	0.54	
919	55-8			0.50	108.5	0.553	97.0	19.9	31.3	25.4	1.03	0.39	
933	55-8		Agrilon	0.01	111.7	0.507	96.4	18.1	28.8	31.5	1.93	0.70	
935	55-8			0.05	111.8	0.507	97.2	18.2	26.9	[illegible]	1.90	0.69	
936	55-8			0.10	[illegible]	0.504	97.6	18.2	27.2	27.3	1.89	0.69	
937	55-8			0.50	110.8	0.520	96.9	18.7	23.4	15.4	0.87	0.32	
			CATIONS										
952	55-10	Portsmouth SAND	Iron - $Fe\,Cl_3$		104.5	0.677	91.8	19.3	22.2	5.6	0.12	0.29	b All salt treatments less than 0.5% of dry soil weight. [illegible] of each salt was added to saturate the soil's ion exchange capacity with the salt's cations. The mixtures were then washed and dried before molding. Molding water manually blended until uniform mixture obtained. Mixture compacted, saturated, and frozen.
955	55-10		Iron - $Fe_2(SO_4)_3$		97.9	0.740	92.5	25.0	56.8	63.7	1.68	2.56	
953	55-10		Barium - $Ba\,Ac_2$		107.9	0.578	99.0	18.8	52.4	76.8	1.63	1.22	
954	55-10		Potassium - KCl		107.6	0.582	90.5	19.3	41.4	95.5	3.06	2.13	
1008	55-9	Fairbanks SILT	Iron - $Fe\,Cl_3$		100.8	0.657	87.5	21.5	31.3	21.2	1.97	0.88	
[illegible]	55-9		Iron - $Fe_2(SO_4)_3$		96.6	0.730	89.6	24.4	29.9	20.6	1.84	0.88	
[illegible]	55-9		Barium - $Ba\,Ac_2$		101.4	0.648	96.2	20.5	55.6	47.7	2.11	1.91	
1010	55-9		Potassium - KCl		98.4	0.698	90.8	21.3	32.6	22.2	1.39	0.65	
957	55-10	Loring TILL	Iron - $Fe\,Cl_3$		120.2	0.382	93.7	11.1	13.6	5.6	0.12	0.05	
960	55-10		Iron - $Fe_2(SO_4)_3$		126.9	0.344	88.4	11.1	21.8	24.9	1.14	0.44	
958	55-10		Barium - $Ba\,Ac_2$		127.2	0.341	86.1	10.5	37.7	56.4	1.53	1.20	
959	55-10		Potassium - KCl		124.4	0.366	83.6	11.2	20.3	27.7	1.56	0.52	
975	55-10	Waste CLAY	Iron - $Fe\,Cl_3$		90.5	0.778	93.0	28.0	32.4	5.5	0.25	0.12	
978	55-10		Iron - $Fe_2(SO_4)_3$		91.5	0.759	95.4	28.0	56.2	53.3	0.68	1.32	
976	55-10		Barium - $Ba\,Ac_2$		94.3	0.706	87.8	24.0	42.4	40.8	1.96	0.97	
977	55-10		Potassium - KCl		96.0	0.676	82.9	21.7	35.4	24.1	1.27	0.62	
766	55-1	Boston Blue CLAY	Iron - $Fe\,Cl_3$		90.7	0.913	84.7	27.8	58.5	51.8	1.24	1.19	
947	55-10		Iron - $Fe\,Cl_3$		104.0	0.667	97.8	23.5	26.0	[illegible]	0.36	0.20	
950	55-10		Iron - $Fe_2(SO_4)_3$		92.2	0.880	92.7	29.4	39.4	21.2	1.01	0.57	
763	55-1		Lead - $Pb\,Ac_2$		81.6	1.049	90.6	34.2	71.0	58.6	1.39	1.56	
945	55-10		Barium - $Ba\,Ac_2$		101.1	0.709	90.5	23.1	39.5	36.7	1.94	1.79	
949	55-10		Potassium - KCl		94.5	0.835	94.5	28.4	47.2	35.4	1.96	1.15	
765	55-1		Mercury - $Hg\,Cl_2$		104.6	0.654	87.9	20.7	32.7	29.6	1.52	0.70	
970	55-10	Fargo CLAY	Iron - $Fe\,Cl_3$		88.2	0.952	90.8	31.3	33.3	[illegible]	0.15	1.05	
[illegible]	55-10		Iron - $Fe_2(SO_4)_3$		93.8	0.835	88.4	26.8	26.2	1.6	0.05	0.29	
971	55-10		Barium - $Ba\,Ac_2$		100.4	0.715	94.9	24.6	27.6	13.8	0.79	0.62	
972	55-10		Potassium - KCl		95.2	0.809	90.3	26.5	28.5	[illegible]	0.23	1.15	
1012	55-9	Niagara Falls CLAY	Iron - $Fe\,Cl_3$		90.4	0.917	89.1	29.5	34.9	[illegible]	[illegible]	[illegible]	
[illegible]	55-9		Barium - $Ba\,Ac_2$		97.7	0.775	91.0	25.4	30.3	5.4	0.98	0.65*	
[illegible]	55-9		Potassium - KCl		91.8	0.887	94.4	40.2	45.9	44.4	2.09	1.34*	
			WATERPROOFERS										
[illegible]	55-1	Boston Blue CLAY	SC-50	0.01	102.3	0.695	99.4	22.3	42.7	41.2	[illegible]	[illegible]	
[illegible]	55-1			0.05	101.6	0.707	90.2	23.0	39.6	37.6	[illegible]	1.06	
[illegible]	55-1			0.10	105.1	0.650	90.4	21.2	29.1	24.1	1.04	[illegible]	
[illegible]	55-1			0.50	107.1	0.620	78.2	17.3	22.9	[illegible]	[illegible]	[illegible]	
[illegible]	55-1			1.00	107.1	0.638	77.4	14.4	22.9	10.6	[illegible]	[illegible]	

* No untreated specimen of Niagara Falls Clay in Tray 55-9. Heave ratios based on average of average rates of heave of standard size specimens natural gradation, 1.50 mm/day.
General Note: See last sheet of this table for notes referred to by numbers in parentheses.

Table AII (cont'd).

Specimen Number	Tray Number	Soil	Additive	Percent	Dry Unit Weight, pcf (1)	Void Ratio (1)	Percent Saturation at Start of Test	Avg. Water Content, % (2) Before Freezing	Avg. Water Content, % (2) After Freezing	Percent Heave (3)	Avg. Rate of heave, mm/day	Rate of heave Ratio	Notes on Specimen Preparation
			WATERPROOFERS, Continued										
CN- 731	55-1	Boston Blue CLAY	Sodium methyl ethyl propyl siliconate	0.05	103.0	0.683	87.6	21.5	32.4	27.7	1.52	0.70	a Waterproofers added to water and manually blended with soil and [illegible] Mixture [illegible] then dried at [illegible] brought to water content [illegible] for soil plus additive, compacted, saturated, and frozen.
732	55-1			0.10	103.3	0.675	88.1	21.5	33.6	23.8	1.35	0.62	
733	55-1			0.50	105.3	0.646	89.0	16.0	20.0	7.2	0.31	0.14	
734	55-1			1.00	105.8	0.640	83.5	19.2	20.7	6.8	0.28	0.13	
741	55-1		Potassium Phenyl Siliconate	0.05	101.7	0.705	95.3	24.3	36.0	31.5	1.14	0.53	
742	55-1			0.10	104.3	0.662	93.6	22.3	33.5	34.1	1.95	0.90	
744	55-1			0.50	101.2	0.650	91.0	22.3	30.3	21.6	0.80	0.37	
745	55-1			1.00	96.2	0.802	74.7	21.5	27.9	11.3	0.54	0.25	
746	55-1		Volan	0.01	102.5	0.691	89.1	22.7	35.7	32.4	1.84	0.85	
747	55-1			0.05	102.6	0.690	92.0	22.8	36.3	32.5	1.75	0.81	
748	55-1			0.10	105.2	0.637	89.[illegible]	20.6	34.3	31.9	1.53	0.70	
749	55-1			0.50	104.8	0.654	89.0	20.9	29.0	19.9	0.89	0.41	
751	55-1			1.00	97.1	0.796	86.8	24.5	23.4	3.2	0.20	0.09	
757	55-1		Guilon	0.05	103.3	0.679	80.5	19.7	36.2	30.2	1.73	0.80	
758	55-1			0.10	104.5	0.682	98.6	21.8	35.4	35.7	2.14	0.99	
759	55-1			0.50	102.2	0.697	98.9	24.9	38.9	32.5	2.10	0.97	
760	55-1		Carbowax Peg 6000	0.10	90.3	0.801	100	28.8	48.3	41.5	2.07	0.95	
761	55-1			0.50	95.7	0.911	84.0	24.5	34.8	39.3	1.96	0.90	
762	55-1			1.00	96.4	0.798	96.3	24.8	32.9	14.2	0.86	0.40	
1051	55-11		Arquad 2HT	0.10	103.3	0.676	88.2	21.5	38.6	30.3	2.68	2.46	
1052	55-11		Armeen 18D	0.10	103.2	0.680	91.5	22.9	39.6	38.2	2.75	2.53	
991	55-9	New Hampshire SILT	Potassium Phenyl Siliconate	0.05	98.5	0.736	89.4	24.0	38.2	34.4	2.73	1.20	
992	55-9			0.10	99.7	0.714	84.3	22.0	41.2	37.9	3.60	1.58	
993	55-9			0.50	100.2	0.689	84.7	21.5	26.4	9.3	1.03	0.45	
994	55-9			1.00	98.3	0.739	84.4	22.8	30.9	17.4	1.73	0.76	
995	55-9		Guilon	0.01	96.[illegible]	0.766	86.4	24.2	49.1	47.9	2.98	1.30	
1049	55-11		Arquad 2HT	0.10	99.7	0.714	80.8	21.1	38.1	32.2	2.96	0.84	
1050	55-11		Armeen 18D	0.10	100.4	0.702	90.6	23.2	41.5	39.5	1.86	1.10	
820	55-8	Fort Belvoir Sandy CLAY	Sodium methyl ethyl propyl siliconate	0.01	109.5	0.538	100	19.9	30.0	30.8	2.02	0.74	
821	55-8			0.05	108.2	0.557	100	20.6	29.2	28.6	1.78	0.65	
822	55-8			0.10	107.7	0.564	96.8	20.2	29.9	27.0	1.08	0.39	
823	55-8			0.50	114.4	0.472	98.1	17.2	15.4	4.5	0.32	0.12	
825	55-8		Potassium Phenyl Siliconate	0.01	109.7	0.535	100	19.8	29.6	30.2	1.89	0.69	
826	55-8			0.05	108.1	0.557	97.0	20.0	30.1	29.9	1.99	0.73	
827	55-8			0.10	108.7	0.549	98.1	19.9	30.1	30.8	1.93	0.70	
828	55-8			0.50	108.2	0.557	96.0	19.8	27.5	28.3	1.65	0.60	
1053	55-11		Arquad 2HT	0.10	109.9	0.533	90.8	17.9	26.7	26.7	1.63	1.06	
1054	55-11		Armeen 18D	0.10	109.6	0.536	84.0	16.7	27.0	29.6	1.91	1.25	
			DISPERSANTS										
774	55-2	Boston Blue CLAY	Sodium Tripolyphosphate	0.10	91.1	0.903	87.0	28.3	53.8	49.5	2.95	1.20	
775	55-2			0.50	87.9	0.974	84.6	29.6	41.6	19.9	1.14	0.47	
776	55-2			1.00	86.8	0.996	94.4	26.3	37.0	15.1	0.79	0.32	

General Note: See last sheet of this table for notes referred to by numbers in parentheses.

Table AII (cont'd).

Specimen Number	Tray Number	Soil	Additive	Percent	Dry Unit Weight pcf (1)	Void Ratio (1)	Percent Saturation at Start of Test	Avg. Water Content, % (2) Before Freezing	Avg. Water Content, % (2) After Freezing	Percent Heave (3)	Avg. Rate of Heave, mm/day	Rate of Heave Ratio (4)	Notes on Specimen Preparation
			DISPERSANTS (Continued)										
CM- 962	55-10		Daxad 21	0.05	103.0	0.683	94.2	23.1	38.6	33.1	1.79	1.00	(a) Dispersants added to molding water, manually blended with soil until uniform mixture obtained. Mixture equilibrated for a day or more, compacted at water content approximating optimum for the soil plus additive, saturated, and frozen.
963	55-10			0.10	110.4	0.571	93.9	17.2	32.8	30.9	1.46	0.82	
964	55-10			0.50	[illegible]	0.671	91.6	20.5	35.7	34.7	1.88	1.05	
965	55-10			1.00	103.5	0.675	91.7	22.3	36.3	32.5	1.64	0.92	
752	55-1		Lignosol	0.05	98.1	0.768	96.6	23.9	43.3	39.9	1.97	0.91	
753	55-1			0.10	100.6	0.724	96.4	25.1	37.9	28.6	1.53	0.71	
754	55-1			0.50	106.7	0.626	91.2	20.5	27.3	16.7	0.98	0.45	
755	55-1			1.00	104.0	0.568	89.4	21.5	30.7	23.2	1.23	0.57	
983	55-9	New Hampshire SILT	Daxad 21	0.05	101.3	0.687	86.0	21.6	79.8	111.8	7.70	3.33	
984	55-9			0.10	95.7	0.795	87.6	25.1	40.6	33.8	1.95	0.85	
985	55-9			0.50	97.5	0.753	91.3	22.3	42.8	30.6	2.08	0.91	
986	55-9			1.00	97.7	0.749	87.4	23.9	28.3	10.9	0.93	0.41	
997	55-9		Lignosol	0.05	95.0	0.798	86.9	25.3	39.0	27.9	2.23	0.98	
998	55-9			0.10	98.1	0.742	95.9	25.3	38.2	26.4	2.69	1.18	
999	55-9			0.50	95.7	0.785	96.3	24.7	43.9	39.6	3.53	1.55	
1000	55-9			1.00	96.1	0.779	91.7	23.2	36.3	21.2	1.30	0.57	
803	55-8	Fort Belvoir Sandy CLAY	Tamol 731	0.01	110.5	0.525	97.6	19.0	25.7	24.7	1.94	0.71	
804	55-8			0.05	110.4	0.525	95.4	18.6	24.2	19.3	1.45	0.53	
805	55-8			0.10	111.0	0.517	100.0	19.2	23.0	16.1	1.06	0.39	
806	55-8			0.50	115.0	0.464	99.1	15.3	13.8	0.6	0.31	0.11	
807	55-8			1.00	111.3	0.476	85.9	15.2	13.2	0.3	0	0	
810	55-8		Daxad 21	0.01	109.1	0.543	94.9	19.1	31.5	33.4	1.90	0.69	
811	55-8			0.05	107.9	0.561	98.7	20.5	30.5	29.6	1.86	0.68	
812	55-8			0.10	[illegible]	0.534	98.7	19.5	26.4	25.1	1.70	0.62	
813	55-8			0.50	[illegible]	0.535	95.0	19.8	19.4	9.6	0.55	0.20	
814	55-8			1.00	113.9	0.452	97.2	16.3	14.3	2.2	0.13	0.05	
815	55-8			1.00	112.5	0.496	94.0	17.3	16.2	2.9	0.25	0.09	
966	55-10		Daxad 21	0.05	113.0	0.517	86.2	16.5	30.1	32.5	1.49	0.71*	
967	55-10			0.10	115.0	0.452	90.3	15.1	22.9	25.7	1.29	0.62*	
968	55-10			0.50	[illegible]	0.417	93.7	14.5	15.7	12.9	0.64	0.31*	
969	55-10			1.00	120.1	0.402	89.5	13.3	15.2	6.4	0.21	0.10*	

* No untreated specimens of Fort Belvoir sandy clay in Tray 55-10. Heave ratios based on 4-year average of average rates of heave, 2.10 mm/day.

NOTES: (1) Dry unit weight and void ratio of compacted soil-plus-additive mixture after saturation. All miniature specimens prepared from minus No. 10 sieve material. Compaction: 4 layers, 20 tamps/layer, with 40 lb. spring tamper.
(2) Water content based on weight of soil and additive.
(3) Based on original height of frozen portion.
(4) Rate of heave ratio = $\frac{\text{avg. rate of heave of treated specimen}}{\text{avg. rate of heave of untreated specimen}}$
Unless otherwise noted heave ratios are based on the average of the average rates of heave of untreated specimens in tray. See Table A-1 for data on untreated basic soils.

Table AIII. Tests for effect of additives (standard-size specimens) (open system).[1]

Specimen Number	MATERIAL (Unified Soil Classification System) Description	Symbol	ADDITIVE Name	Percent (2)	GRAIN SIZE Max. Size in.	mm - % Finer 4.76	0.42	0.074	0.02	FREEZING TEST RESULTS Percent Heave (3)	Average Rate of Heave mm./day	Heave Ratio (4)	After Saturation Dry Unit Weight pcf	Void Ratio	(5) Permeability x 10^{-4} cm./sec.	Saturation at Start of Test %	Average Water Content, % Molding	Before Freezing	After Freezing	(6) Atterberg Limits L.L.	P.I.
LSG-1A	Loring Silty Sandy GRAVEL Lab. Ser. No. 49-49	GW-GM	None	-	3/4	47	17	9.5	6.8	61.1	2.9	-	137	0.234	0.3	100	[illegible]	[illegible]	[illegible]	Non-plastic	
LSG-2A			Agrilon (7)	0.01	3/4	47	17	9.5	6.8	58.8	2.1	0.73	135	0.251	-	100	6.0	9.8	[illegible]	-	-
LSG-3A			Agrilon	0.05	3/4	47	17	9.5	6.8	35.6	1.7	0.59	135	0.251	-	[illegible]	6.0	9.7	23.0	-	-
LSG-4A			Agrilon	0.10	3/4	47	17	9.5	6.8	16.9	0.9	0.31	133	0.270	-	97	6.0	10.1	15.3	-	-
LSG-5A	Loring Silty Sandy GRAVEL (Graded to contain approx. 12% finer than 0.02 mm.) Made from Lab. Ser. No. 49-49	-	None	-	3/4	77	29	16	12	70.4	3.8	-	139	0.215	-	100	6.0	[illegible]	33.2	-	-
LSG-6A			Agrilon	0.01	3/4	77	29	16	12	46.6	2.6	0.69	136	0.242	-	[illegible]	6.0	[illegible]	[illegible]	-	-
LSG-7A			Agrilon	0.05	3/4	77	29	16	12	37.7	2.0	0.53	136	0.242	-	100	6.0	9.7	[illegible]	-	-
LSG-8A			Agrilon	0.10	3/4	77	29	16	12	29.6	1.5	0.40	137	0.234	-	100	[illegible]	9.3	[illegible]	-	-
LSG-9A	Loring Silty Sandy GRAVEL (Graded to contain approx. 4% finer than 0.02mm.) Made from Lab. Ser. No. 49-49	-	None	-	3/4	25	9.6	5.3	4.0	24.2	0.9	-	132	0.280	-	98	3.0	10.5	[illegible]	-	-
LSG-10A			Agrilon	0.01	3/4	25	9.6	5.3	4.0	30.8	1.4	1.56	125	0.351	-	97	3.0	13.0	25.0	-	-
LSG-11A			Agrilon	0.05	3/4	25	9.6	5.3	4.0	19.1	0.8	0.89	124	0.362	-	99	[illegible]	[illegible]	[illegible]	-	-
LSG-12A			Agrilon	0.10	3/4	25	9.6	5.3	4.0	14.5	1.0	1.11	125	0.351	-	100	[illegible]	[illegible]	17.2	-	-
BH-50A	Lab. Ser. No. 49-46		Agrilon	0.05	-	100	100	99	77	22.7	3.4	0.92	105	0.629	-	95	15.0	21.6	32.1	-	-
BH-51A			Agrilon	0.10	-	100	100	99	77	58.3	6.9	1.86	106	0.612	-	100	15.0	21.7	46.9	-	-
BH-1A (8)	Clayey Gravelly SAND (Breed's Hill Till) Lab. Ser. No. 49-91	SC	None	-	3/4	76	60	41	24	7.3	0.6	-	139	0.239	-	94	7.4	[illegible]	[illegible]	24	11
BH-2A			Portland Cement	2	3/4	76	60	41	24	2.3	0.2	0.33	136	[illegible]	-	100	7.4	9.5	[illegible]	-	-
BH-3A -			Portland Cement & Daxad 21 (9)	2 1.5	3/4	76	60	41	24	6.8	0.3	0.50	136	0.270	-	100	7.4	9.5	10.6	-	-
BH-4A -			Portland Cement & Daxad 21	5 1.0	3/4	76	60	41	24	9.0	0.4	0.67	134	0.295	-	100	[illegible]	10.2	[illegible]	-	-

NOTES:
(1) Standard-size specimens 5.91 in. diameter, 6 in. high, load pressure 0.5 lbs./sq. in.
(2) Percent on dry soil weight, Agrilon added to molding water and manually blended with soil until uniform mixture obtained.
(3) Based on original height of frozen portion.
(4) Ratio of average rate of heave of treated soil to average rate of heave of untreated soil.
(5) At 10° C.
(6) On material passing U. S. Std. Sieve No. 40.
(7) Sodium Polyacrylate, an aggregant.
(8) Specimens BH-1A through BH-4A each mixed in mechanical mixer a total of 12 minutes. Cement and Daxad added to soil at water content = 6.4%. Soil water content increased to 7.4% prior to compaction. Specimens cured about 7 days at room temperature and humidity. Dry unit weight and void ratio are for compacted soil-plus-additive mixture.
(9) Daxad 21: formaldehyde-condensed naphthalene sulfonate.

Table AIV. Tests for effect of additives: dispersants (standard-size specimens) (open system).[1]

Specimen Number	Material (Unified Soil Classification System): Description	Symbol	Additive: Name	Additive: Percent (2)	Grain Size: Max. Size in.	mm - % Finer: 4.76	0.42	0.074	0.02	Freezing Test Results: Percent Heave (3)	Average Rate of Heave mm./day	Heave Ratio (4)	After Saturation: Dry Unit Weight pcf	Void Ratio	(5) Permeability x 10⁻⁴ cm./sec.	Saturation at Start of Test %	Average Water Content, %: Molding	Before Freezing	After Freezing	(6) Atterberg Limits: L.L.	P.I.
DFB-3	Dow Sandy GRAVEL	GM	None	-	3/4	42	13	4.9	2.4	13.8	1.0	-	131	0.265	16.0	95	5.0	10.3	13.6	Non-Plastic	
DFB-4	Test Embankment (B-11)		None	-	3/4	42	13	4.9	2.4	15.7	1.1	-	131	0.285	17.5	99	5.0	10.9	14.7	Non-Plastic	
DFB-5A			TSPP (7)	0.30	3/4	42	13	4.9	2.4	6.0	0.4	0.36	131	0.285	-	92	5.0	9.9	11.1	-	-
PBJ-6	Sandy GRAVEL	GM	None	-	3/4	38	18	4.0	1.7	51.8	3.4	-	140	0.212	1.6	100	5.0	7.8	27.6	Non-Plastic	
PBJ-17A	PBJ Greenland (TP-250)		TSPP	0.30	3/4	38	18	4.0	1.7	3.9	0.2	0.06	143	0.187	-	96	3.0	7.4	8.3	-	-
DFSB-2	Dow Silty Sandy GRAVEL	GW-GM	None	-	3/4	49	17	8.0	3.2	20.5	1.1	-	134	0.251	4.6	100	5.0	10.0	16.8	Non-Plastic	
DFSB-4A	Test Embankment (B-18)		TSPP	0.30	3/4	49	17	8.0	3.2	10.1	0.6	0.55	134	0.251	-	100	5.0	10.0	10.9	-	-
RC-1	Ellsworth Silty Gravelly SAND	SW-SM	None	-	1½	57	30	12	8.7	16.4	1.7	-	137	0.252	0.048	98	6.0	9.1	13.9	19	2
RC-3A	Lab. Ser. No. 49-11		TSPP	0.30	1½	57	30	12	8.7	2.5	0.1	0.06	137	0.252	-	96	5.0	8.9	8.1	-	-
CL-1	Clinton County Silty Clayey GRAVEL	GM-GC	None	-	1½	54	30	20	15	65.6	4.6	-	129	0.316	0.10	100	9.0	11.7	28.9	25	7
CL-3A	Lab. Ser. No. 49-8 & 49-8A		TSPP	0.30	1½	53	25	15	9.0	7.0	0.5	0.11	129	0.316	-	100	5.0	11.8	12.9	-	-
SPK-1	Spokane Gravelly SAND	SW-SM	None	-	1½	68	11	7.0	3.5	13.6	1.1	-	128	0.365	32.0	100	6.0	13.0	15.8	Non-Plastic	
SPK-[illegible]A	Lab. Ser. No. 49-21		TSPP	0.30	1½	69	11	7.0	3.5	9.0	0.4	0.36	128	0.365	-	100	5.0	13.7	15.3	-	-
LIN-4	Lincoln Gravelly SAND	SP-SM	None	-	1	71	27	7.8	5.0	19.6	1.2	-	132	0.253	-	98	7.0	9.3	15.5	Non-Plastic	
LIN-5A	Lab. Ser. No. 49-102		TSPP	0.30	3/4	67	24	6.3	5.0	1.0	0.2	0.17	134	0.233	-	93	4.8	9.5	8.6	-	-
FAS-1	Fairchild Silty Clayey Gravelly SAND	SM-SC	None	-	3/4	76	29	17	9.5	29.0	3.2	-	131	0.320	-	94	4.5	10.7	24.8	22	3
FAS-5A	Lab. Ser. No. 49-60		TSPP	0.30	3/4	88	33	19	10	16.0	1.1	0.34	131	0.320	-	91	6.3	10.4	16.2	-	-
PAFB-6	Portsmouth Silty Gravelly SAND	SM	None	-	3/4	68	45	23	14	81.8	5.6	-	127	0.376	-	100	8.5	12.3	44.1	Non-Plastic	
PAFB-3A	Lab. Ser. No. 49-54		TSPP	0.30	3/4	68	45	23	14	27.8	1.3	0.23	130	0.295	-	94	5.0	11.7	21.8	-	-
SF-1	Sioux Falls Silty Clayey Gravelly SAND	SM-SC	None	-	1	71	28	26	9.0	16.6	1.7	-	131	0.285	0.16	100	4.0	10.6	17.0	24	6
SF-2A	Lab. Ser. No. 49-17		TSPP	0.30	1	75	28	25	8.0	4.3	0.2	0.12	128	0.316	-	100	11.1	12.0	11.8	-	-
PT-1	Patterson Silty Clayey Gravelly SAND	SM-SC	None	-	1½	62	33	22	15	44.4	3.3	-	135	0.259	0.001	100	5.0	9.7	26.0	22	6
PT-3A	Lab. Ser. No. 49-9		TSPP	0.30	1½	63	34	21	15	5.1	0.2	0.06	137	0.240	-	100	4.7	8.9	9.5	-	-
LST-13A	Loring Clayey Sandy GRAVEL (Glacial Till) Lab. Ser. No. [illegible] (Limestone, Me., Subgrade Frost Test Section. See Note (9) for Details of Tests	GC	None	-	2	68	52	41	30	51.7	4.5	-	126	0.351	-	93	12.0	12.0	26.2	[illegible]	6
LST-11A			Quadrafos	0.30	2	68	52	41	30	4.9	0.5	0.11	129	0.320	-	100	12.0	12.0	13.2	-	-
PAFB-1A	Portsmouth Sandy CLAY	CL	None	-	-	100	96	89	33	47.1	4.0	-	113	0.490	-	92	16.0	16.3	37.2	25	12
PAFB-2A	Lab. Ser. No. [illegible]		Quadrafos	0.10	-	100	98	91	33	43.4	3.4	0.85	111	0.519	-	100	16.0	17.4	36.3	-	-
[illegible]-52A	Lab. Ser. No. 49-46		Quadrafos	0.10	-	100	100	99	77	23.5	2.5	0.68	109	0.570	-	[illegible]	15.0	20.4	24.5	-	-
[illegible]-53A			Quadrafos	0.50	-	100	100	99	77	14.8	1.6	0.43	108	0.582	-	95	15.0	19.5	[illegible]	-	-
[illegible]	[illegible] Reservoir Sandy CLAY	CL	None	-	3/4	95	[illegible]	64	43	25.0	1.3	-	115	0.461	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Lab. Ser. [illegible]		Quadrafos	0.30	3/4	95	[illegible]	54	43	13.2	[illegible]	0.46	114	0.495	-	[illegible]	[illegible]	16.8	[illegible]	-	-

NOTES:

(1) Standard-size specimens [illegible] in. diameter, 6 in. high, surcharge 0.5 lbs./sq.in.
(2) Percent [illegible] soil weight. Dispersants added to molding water and manually blended with soil until uniform mixture obtained.
(3) Based on original height of frozen portion.
(4) Ratio of average rate of heave of treated soil to average rate of heave of untreated soil.
(5) At 10°C.
(6) On material passing U. S. Std. Sieve No. 40.
(7) Tetrasodium Pyrophosphate.
(8) Sodium Tetraphosphate.
(9) Specimens LST-13A and LST-11A [illegible] in. diameter, 12 in. high, no surcharge, not saturated prior to freezing to simulate conditions at field test section.

Table AV. Tests for effect of four cycles of freezing and thawing on dispersant-treated non-plastic soils (standard-size specimens) (open systems).[1]

Specimen Number	MATERIAL (Unified Soil Classification System): Description	Symbol	ADDITIVE: Name	Percent (2)	GRAIN SIZE: Max. Size in.	mm - % Finer: 4.76	0.42	0.074	0.02	FREEZING TEST RESULTS: Freezing Cycle	Percent Heave (3)	Average Rate of Heave mm/day	Heave Ratio (4)	(5) Dry Unit Weight pcf	(5) Void Ratio	(6) Permeability x 10^{-4} cm/sec	Saturation at Start of Test %	Average Water Content, %: Molding	Before Freezing	After Freezing
DFSB-3	Dow Silty Sandy GRAVEL	GW-GM	None	-	3/4	49	17	8.0	3.2	1	18.4	1.2	-	132	0.271	0.2	95	5.[illegible]	1[illegible]	[illegible]
DFSB-5A	Test Embankment (B-18)		TSPP(7)	0.30	3/4	49	17	8.0	3.2	1	2.0	0.2	0.17	134	0.251	-	[illegible]	3.[illegible]	[illegible].8	-
										2	2.7	0.2	0.17	135	0.241					-
										3	2.6	0.1	0.09	135	0.241					-
										4	2.2	0.2	0.17	131	0.250					[illegible]
LSG-37	Loring Silty Sandy GRAVEL	GW-GM	None	-	1	48	9	5.6	4.6	1	34.3	3.1	-	134	0.261	-	100	3.0	9.6	[illegible]
LSG-13A	Lab. Ser. No. 49-30		TSPP	0.30	1	48	9	5.6	4.6	1	5.8	0.3	0.10	134	0.261	-	[illegible]	3.[illegible]	9.[illegible]	-
										2	3.7	0.2	0.06	134	0.261					-
										3	4.3	0.2	0.06	131	0.290					-
										4	2.9	0.2	0.06	132	0.281					[illegible]
LIN-4	Lincoln Gravelly SAND	SP-SM	None	-	1	71	27	7.8	5.0	1	19.6	1.2	-	132	0.252	-	98	7.0	[illegible].3	[illegible]
LIN-6A	Lab. Ser. No. 49-102		TSPP	0.30	3/4	67	27	7.0	5.0	1	0.1	0.1	0.09	132	0.252	-	100	3.0	9.[illegible]	-
										2	0.9	0.1	0.09	132	0.252					-
										3	1.2	0.1	0.09	131	0.262					-
										4	0.8	0.1	0.09	129	0.281					[illegible]
PAFB-8	Portsmouth Silty Gravelly SAND	SM	None	-	3/4	6[illegible]	45	23	14	1	81.8	5.[illegible]	-	127	0.326	-	[illegible]	8.5	12.3	[illegible]
PAFB-4A	Lab. Ser. No. 49-54		TSPP	0.30	3/4	5[illegible]	45	23	14	1	6.6	0.5	[illegible]	13[illegible]	0.296	-	[illegible]	9.0	10.[illegible]	-
										2	7.0	0.8	0.14	131	0.25[illegible]					
										3	11.7	0.5	0.09	130	0.296					-
										4	9.5	0.7	0.12	127	0.326					[illegible]

NOTES:

(1) Standard-size specimens 5.91 in. diameter, 6 in. high, surcharge 0.5 lbs/sq.in.

(2) Percent on dry soil weight. TSPP added to molding water and manually blended with soil until uniform mixture obtained.

(3) Based on original height of frozen soil.

(4) Ratio of average rate of heave of treated soil to average rate of heave of untreated soil.

(5) Dry unit weight and void ratio at beginning of cycle.

(6) At 10°C.

(7) Tetrasodium pyrophosphate.

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13. ABSTRACT
Fifty-two additives to reduce the frost susceptibility of soil were tested on twenty-five soils. The theoretical considerations underlying the choice of additives are discussed. The additives are divided into five groups according to their action in soil: 1) void fillers and cements, 2) aggregants, 3) metallic salts, 4) waterproofers, and 5) dispersants. A number of additives, especially dispersants and polyvalent cation salts, merit further laboratory evaluation. Resins and waterproofers also look promising. Four freeze-thaw cycles on four different dispersant-treated soils tested in the laboratory showed no diminution of effectiveness of treatment. A small-scale field test showed a laboratory-proved dispersant to be effective under field conditions; measurements made over two seasonal freezing cycles showed retention of original effectiveness of the dispersant treatment.

14. KEY WORDS

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